Cycloaddition of *o*-Benzoquinone to a Kinetically Stabilized Cyclobutadiene[1]

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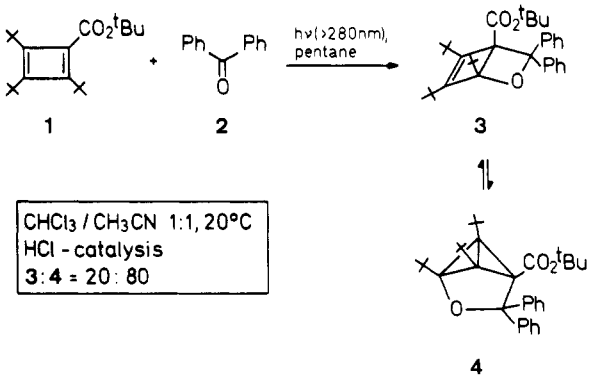
tert-Butyl 2,3,4-tri-*tert*-butylcyclobutadiene-1-carboxylate (**1**) reacts at room temperature with 9,10-phenanthrenequinone (**10a**), 3,5-di-*tert*-butyl-1,2-benzoquinone (**10b**), 1,2-naphthoquinone (**10c**), and tetrabromo- and tetrachloro-1,2-benzoquinones (**10d,e**) to form the dihydrodioxins **11a–e**. Structural assignments were based mainly on ^{13}C NMR studies and an X-ray crystal structure analysis of **11a**. The oxatricycles **12** are assumed to be the initial products of the multistep reaction; **12a** was isolated and **12b** could be unequivocally characterized by NMR spectroscopy. Both compounds isomerize under mild conditions to the apparently more stable dihydrodioxins **11a** and **11b**. In the case of the reaction of **1** with **10b**, a third isomer to which we assign the structure **13** was formed in addition to **12b** and **11b**. We assume that the homocyclopropenylium betaines **14** and **15** are responsible for the course of the apparently kinetically controlled reaction **1** + **10** → **12** as well as the thermodynamically influenced subsequent isomerization **12** → **11**.

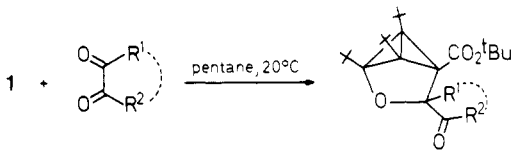
Cycloaddition reactions of aldehydes and ketones with kinetically stabilized cyclobutadienes were, until recently, unknown. The photochemical reaction of benzophenone (**2**) with *tert*-butyl 2,3,4-tri-*tert*-butylcyclobutadiene-1-carboxylate (**1**),[2] which presumably proceeds via a biradical intermediate and yields the 2-oxabicyclo[2.2.0]hex-5-ene **3**,[3,4] led to commencement of developments in this field.



When the heterobicycle **3** is dissolved in 1/1 chloroform/acetonitrile at room temperature (hydrogen chloride catalysis), it sets up an equilibrium with the 3-oxatricyclo[3.1.0.0^{2,6}]hexane **4** (ratio 20:80); the tricyclic isomer **4** can be isolated from the solution. Under the above-mentioned conditions, equilibration occurs again, this time, however, from the tricyclic side.

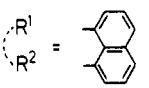
The discovery of this previously unknown equilibrium system prompted us to study the cycloaddition behavior of **1** with reactive carbonyl compounds. First it was found that aldehydes, such as, e.g., acetaldehyde or benzaldehyde, undergo cycloaddition with **1** at room temperature, also in the absence of photochemical excitation, to form the oxabicycles corresponding to **3**.[5,6]

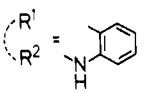
Open chain as well as cyclic α-dicarbonyl compounds such as **5a–d**, in contrast, react with **1** under identical conditions to give the oxatricycles **6**,[7] which, in chloroform



5a, 6a: $R^1 = R^2 = Me$

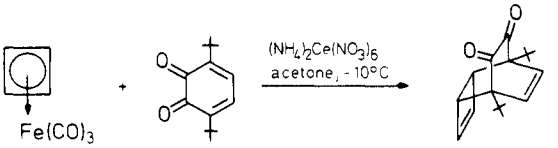
5b, 6b: $R^1 = R^2 = Ph$

5c, 6c: R^1, R^2 = 

5d, 6d: R^1, R^2 = 

at room temperature, are transformed predominantly to the thermodynamically more stable bicyclic isomers.

It has been long known that highly reactive, unsubstituted cyclobutadiene, oxidatively released from the iron tricarbonyl–cyclobutadiene complex **7**, undergoes exclusive [4 + 2] cycloaddition with α,β-unsaturated carbonyl compounds at the C–C double bond of the dienophile.[8] The *o*-quinone **8** also reacts with cyclobutadiene, generated in the same way, by cycloaddition with the 1,3-diene moiety to give **9**[9] and not with one or both of the carbonyl groups.



In the present paper, we report on the reactivity of the kinetically stabilized cyclobutadiene **1** with *o*-quinones. This reaction, however, in contrast to the above mentioned example, takes place exclusively at the carbonyl groups.

(1) Syntheses with Cyclobutadienes. 8. For Part 7, see: Fink, J.; Regitz, M *Chem. Ber.* **1985**, *118*, 2255.
(2) Eisenbarth, P.; Regitz, M. *Chem. Ber.* **1982**, *115*, 3796.
(3) Eisenbarth, P.; Regitz, M. *Angew. Chem.* **1982**, *94*, 935; *Angew Chem., Int. Ed. Engl.* **1982**, *21*, 913; *Angew Chem., Suppl.* **1982**, 2016.
(4) Eisenbarth, P.; Maas, G.; Regitz, M. *J. Am. Chem. Soc.* **1983**, *105*, 5134.
(5) Fink, J.; Regitz, M. *Tetrahedron Lett.* **1984**, *25*, 1711.
(6) See literature cited under ref 1.
(7) **5a–c**: see literature cited under ref 1, **5d**: Fink, J., Regitz, M., unpublished results, University of Kaiserslautern, 1984.
(8) Meinwald, J.; Mioduski, J. *Tetrahedron Lett.* **1974**, *15*, 4137. Groves, J. T.; Bernhardt, C. A. *J. Org. Chem.* **1975**, *40*, 2806. Vedejs, E.; Wu, E. S. C. *J. Am. Chem. Soc.* **1975**, *97*, 4706. Georgescu, E. G.; Gheorghiu, N. D. *Rev. Roum. Chim.* **1977**, *22*, 907; *Chem. Abstr.* **1977**, *87*, 84078*p*.
(9) Paquette, L. A.; Hefferon, G. J.; Samodral, R.; Hanzawa, Y. *J. Org. Chem.* **1983**, *48*, 1262.

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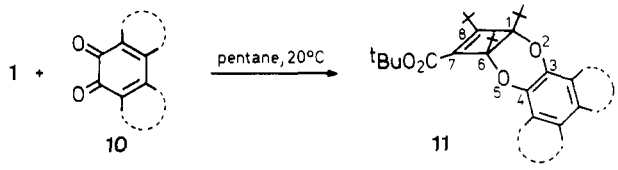
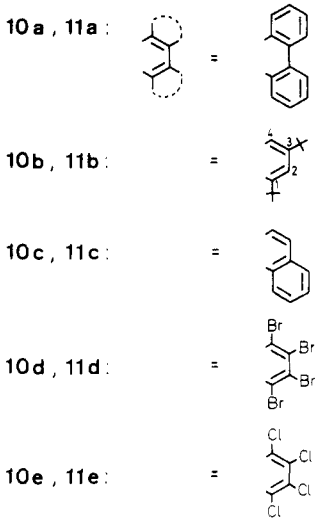
Results

When 1 is allowed to react with the *o*-quinones **10a–e** at 20 °C in pentane, the dihydrodioxin derivatives **11a–e**



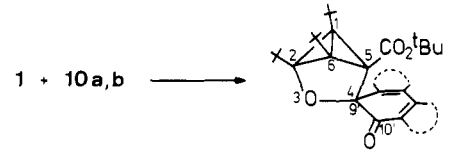
10 11



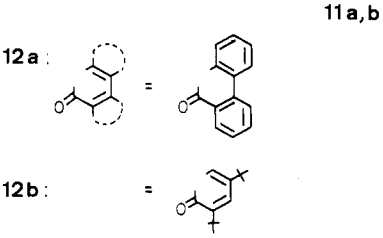
are formed (yields 25–67% with cosideration of the isomer **13**). The structures are assigned mainly on the basis of the ^{13}C NMR spectra; thus, the exception of the ester carbonyl groups, no signals are observed that could be attributed to further carbonyl groups. This indicates that **1** has reacted with both carbonyl groups of **10a–e** cycloaddition process and is in agreement with the appearance of two resonances in the region δ 100.29–107.35 which can only be attributed to the carbon atoms C-1 and C-6.

The two oxygen atoms are responsible for the shift to lower field; the small differences in the chemical shifts of C-1 and C-6 in the individual dihydrodioxins indicate that the reaction must have occurred at two *tert*-butyl-substituted carbons. This is confirmed by the appearance of the resonances of the differently substituted olefinic carbon atoms C-7 and C-8 at widely varying fields (δ 136.79–142.75 and 157.39–165.46).[10] The identical bridging carbon atoms in the dioxetane formed from tetra-*tert*-butylcyclobutadiene and oxygen, which possesses the same structural element as **11a–e**, resonate at δ 108.73.[11] Finally, the resonances of the ester carbonyl carbon atoms of the cycloadducts at relatively high field (δ 165.20–166.53) indicate that the α,β-unsaturated ester group is present in unchanged form. In order to remove last doubts about the constitution of the key substances of this work, an X-ray crystal structure analysis of **11a** was carried out (see later).

It can be shown, at least in the cases of the reactions of **1** with **10a,b**, that the dihydrodioxins **11a,b** are not the primary products of the reaction. Thus, early quenching of the reaction of **1** with phenanthrenequinone (**10a**) results in the isolation of the spirocyclic 3-oxatricyclohexane **12a**; the tricycle **12b** could only be detected by ^1H and ^{13}C NMR spectrometry in the reaction mixture of the cyclobutadiene with the *o*-benzoquinone **10b**. We assume here that the formation of this product involves the 2-carbonyl group of **10b** as this does not suffer steric hindrance from a *tert*-butyl group. There is no evidence here for, e.g., a competitive primary reaction at both CO groups of the *o*-benzoquinone. The reaction of **1** with 1,2-naphthoquinone (**10c**) presents a similar problem where we also assume that only the reactive 2-CO group participates in the primary reaction, as shown in structure **12**, which necessarily results in the formation of **11c**.



12



The oxatricyclohexane **12a** even undergoes quantitative isomerization to **11a** in deuteriochloroform at room temperature (according to ^1H NMR spectroscopy); **12b** behaves similarly to give **11b** when the crude product obtained from the reaction of **1** with **10b** is allowed to stand at room temperature for several days.

From the ^{13}C NMR spectra of **12a** and **12b** it can be seen that the addition of **1** can only have occurred at one CO group of **10a** or **10b** as signals for a further quinone carbonyl group can be observed at δ 200.20 (**12a**) or 200.85 (**12b**). The tricyclic structure of the intermediate is indicated by the appearance of signals at δ 48.48, 49.27, and 64.82 (**12a**) or 45.96, 49.88, and 62.65 (**12b**) which are assigned to the skeletal carbon atoms C-1, C-6, and C-5.[12] The typical olefinic carbon atoms of the isomeric bicycles **11a,b** are missing in the spectra of both tricycles. Further evidence for the primary formation of the tricycles can be found in the ^1H NMR spectrum of **12b**: a significant shift to higher field by about $\Delta\delta$ 0.5 relative to the *o*-quinone **10b** is observed for one of the ring protons, in accord with the removal of one CO group. In contrast, as mentioned previously, on formation of the dihydrodioxin as depicted by **11b**, the resonances of the two protons of the original quinone are shifted to lower field (see Experimental Section).

On reaction of **1** with **10b**, in addition to **12b** and its isomerization product **11b**, a further, oily isomeric product is obtained which, however, in spite of chromatographic work up could not be isolated in analytically pure form. The ^{13}C NMR spectrum, in particular, of this product shows close similarities with that of **11b**. Thus, signals are observed at, among others, δ 102.25 and 103.00 in the region which is typical foor the C-1/C-6 carbon atoms of the dihydrodioxins **11**. As all the other resonances show

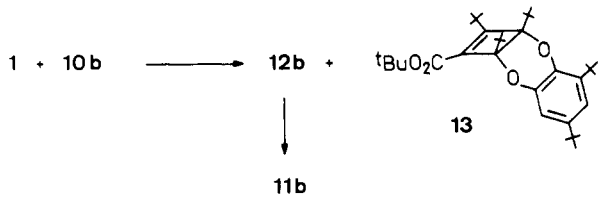
(10) Compare with the ^{13}C NMR data of the two constitutional isomeric adducts from 4-phenyl-1,2,4-triazoline-3,5-dione and **1**: cf. ref 2.

(11) Irngartinger, H.; Riegler, N.; Malsch, K.-D.; Schneider, K. A.; Maier, G. *Angew. Chem.* **1980**, *92*, 214; *Angew. Chem., Int. Ed. Engl.* **1980**, *19*, 211.

(12) This is in accord with the assignment of the ^{13}C NMR data of **4**, the structure of which has been confirmed by an X-ray crystal analysis.[4]

(13) Review: Bally, T.; Masamune, S. *Tetrahedron* **1980**, *36*, 343. See also ref 2.

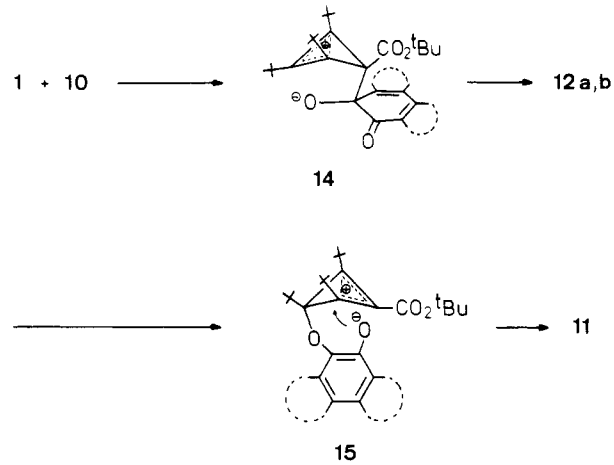
only minor deviations from those of **11b** it would appear to be justified to assume that this product is **13**, an isomer of **11b**.



Considerations on the Mechanism

In Diels–Alder reactions cyclobutadienes can function both as the 1,3-diene as well as the dienophile.[13] From a purely formal point of view, the reaction **1** + **10** → **11** can be considered as a hetero-Diels–Alder reaction in which the antiaromatic system serves as the dienophile and the *o*-quinone as a hetero-1,3-diene.

We assume that the formation of the dihydrodioxins **11** results from a multistep reaction sequence in which the oxatricycle **12** is first formed in a kinetically controlled reaction (see the isolation of **12a** and the NMR evidence for **12b**). The other reactions presumably proceed similarly although the corresponding intermediates could not be detected. Nucleophilic attack of the ester-substituted carbon atom of **1** at one of the carbonyl groups of **10** (in the cases of **10b,c** this should be the sterically less hindered CO group) leads to betaine **14**, the positive charge of which



is subject to a homoaromatic stabilization.[14] Ring closure between oxygen and the carbon atom which becomes C-2 in the product then gives rise to **12**. The driving force for the subsequent rearrangement to **11** (which is apparently the thermodynamically controlled product of the reaction of **1** with **10**) could possibly arise from the aromatization of the original quinoid system. The zwitterionic species **15** may be the intermediate for this isomerization step; **15** is formed by heterolytic cleavage of the C-4/C-5 bond and profits from the above-mentioned aromatization. The reaction sequence is completed by recombination between the enolate oxygen atom and the carbon atom which becomes the bridgehead carbon C-6 in the product to give the dihydrodioxins **11**. The reason for the failure of the cycloaddition of **1** with *o*-Quinones to give an analogous product to **9** may be due to the sterical hindrance of **1**.

X-ray Crystal Structure of 11a. The X-ray structural analysis of **11a** confirms the structure first suggested on the basis of spectroscopic studies for the products from the reactions of **1** with **10**. Thus, among others, the attack of the quinone at two di-*tert*-butyl-substituted carbon atoms of the antiaromatic system is corroborated; also, as seen from Figure 1, **11a** has the endo configuration in the crystal state.

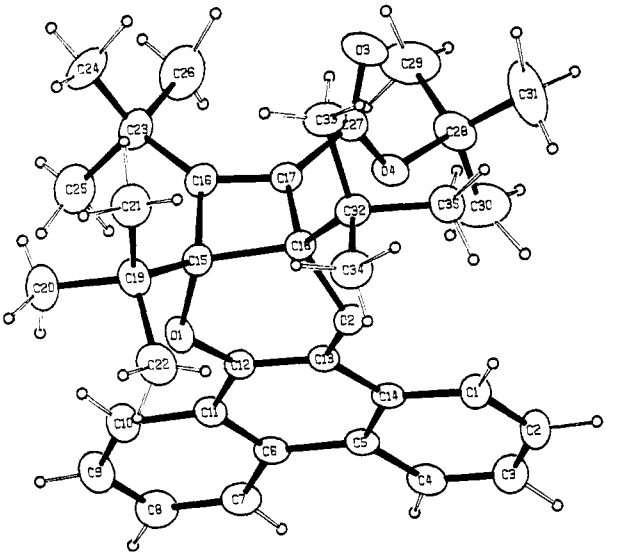


Figure 1.

When the geometry of the cyclobutene unit of **11a** is compared with that of other cyclobutenes,[15] a significant stretching of the two di-*tert*-butyl-subtituted bonds C15–C18 (1.632 Å vs. average length of 1.573 Å[15]) and C15–C16 (1.548 Å vs. average length of 1.514 Å[15]) is noticeable. The reason for this is presumably to be found in the steric hindrance of the *tert*-butyl groups which additionally cause a marked folding of the four-membered ring along its diagonal (11.6°). This has also been observed for other sterically hindered cyclobutenes.[16-18]

The C16–C17 double bond is relatively short (1.327 Å), indicating lack of conjugation with the ester group (average values from ref 15 for cyclobutene double bonds: conjugated with ester groups 1.349 Å, nonconjugated 1.323 Å). This is also clearly visible from Figure 1 which shows that the ester group does not lay in the plane of the four-membered ring; the torsional angle C-16–C-17–C-27–O-3 is 72.3° (for selected structural parameters of **11a**, see Table I).

Experimental Section

Melting points are uncorrected and were determined with a Mettler FP 61 apparatus (heating rate 3 °C/min). Microanalyses were obtained on a Perkin-Elmer Analyzer 240. IR spectra were recorded with a Beckman IR 20A spectrophotometer. ^{1}H NMR spectra were obtained using Varian EM 360 and EM 390 spectrometers with tetramethylsilane as internal standard. ^{13}C NMR spectra were recorded on a Bruker WP 200 spectrometer also with tetramethylsilane as internal standard. Mass spectra were obtained using a Varian MAT 311 spectrometer (ionization energy 70 eV).

The cyclobutadiene **1** is separated from byproducts in vacuum before use;[2] the quinones **10a–e** are commercial products. All reactions of **1** were performed in an argon atmosphere (Schlenk tube technique); solvents used were anhydrous and were previously distilled and stored under argon.

General Procedure for the Reaction of the Cyclobutadiene

(14) On the existence of homocyclopropenylium cations, see: Haddon, R. C.; Raghavachari, K. *J. Am. Chem. Soc.* **1983**, *105*, 118 and references cited therein.

(15) Allen, F. H. *Acta Crystallogr. Sect. B* **1984**, *B40*, 64.
(16) Hanson, A. W. *Cryst. Struct. Commun.* **1981**, *10*, 319.
(17) Lerbscher, J. A.; Trotter, J. *J. Cryst. Mol. Struct.* **1971**, *1*, 355.
(18) Muir, K. M.; Sim, G. A. *J. Chem. Soc. B* **1968**, 667.

Table I. Selected Bond Lengths (Å) and Angles (deg) in 11a (Standard Deviations Are in Parentheses)

C-12–C-13	1.343 (3)	C-16–C-15–C-18	84.3 (2)
C-12–O-1	1.359 (3)	C-15–C-16–C-17	93.8 (2)
C-13–O-2	1.374 (3)	C-16–C-17–C-18	97.0 (2)
C-15–O-1	1.468 (3)	C-15–C-18–C-17	83.8 (2)
C-15–C-16	1.548 (4)	C-12–O-1–C-15	120.3 (2)
C-15–C-18	1.632 (3)	C-13–O-2–C-18	115.8 (2)
C-16–C-17	1.327 (3)	O-1–C-15–C-18	110.5 (2)
C-17–C-18	1.518 (3)	O-2–C-18–C-15	112.6 (2)
C-18–O-2	1.445 (3)	O-1–C-12–C-13	121.4 (2)
		O-2–C-13–C-12	119.5 (2)

1 with the *o*-Quinones 10a–e. To a solution of 1 in 5 mL of pentane is added in portions an equimolar amount of the appropriate *o*-quinone **10** and the mixture is stirred at room temperature until the brown color disappears. Unreacted quinone is filtered off and the filtrate is concentrated at 30 °C (15 torr) (for further details of workup see under the individual products).

***tert*-Butyl 1,6,8-Tri-*tert*-butyl-3,4-(9,10-phenanthro)-2,5-dioxabicyclo[4.2.0]octa-3,7-diene-7-carboxylate (11a).** Amounts: 640 mg (2.00 mmol) of cyclobutadiene 1, 416 mg (2.00 mmol) of 9,10-phenanthrenequinone (**10a**). Reaction time: 10 min. The yellow oily residue is treated with 2 mL of petroleum ether (30–75 °C) whereupon crystallization begins. Suction filtration and washing with cold petroleum ether (30–75 °C) gives 240 mg (25%) of **11a** as colorless crystals with mp 177 °C: IR (KBr) 1706, 1648, 1600 cm^{-1}, ^1H NMR ($CDCl_3$) δ 1.04, 1.05, 1.46 (3 s, 9 H each), 1.53 (br s, 9 H), 7.47–8.73 (m, 8H); ^{13}C NMR ($CDCl_3$) δ 27.31, 29.90 (br),[19] 30.08 [$(H_3C)_3C$], 33..93, 37.78, 39.11 [$(H_3C)C$], 81.91 [$OC(CH_3)_3$], 100.79, 105.91 (C-1, C-6, 119.41–134.84 (Ar C), 141.59 (C-7), 157.45 (C-8), 166.53 (CO ester); MS, *m/e* 528 (12%, M^+), 320 (22%, M^+ – **10a**), 264 (24%, M^+ – **10a** – C_4H_8), 208 (100%, **10a**), 207 [31%, $(C_4H_9)_3C_3^+$]. Anal. Calcd for $C_{35}H_{44}O_4$: C, 79.51; H, 8.39. Found: C, 79.4; H, 8.38.

***tert*-Butyl 1,6,8-Tri-*tert*-butyl-3,4-(1,3-di-*tert*-butylbenzo)-2,5-dioxabicyclo[4.2.0]octa-3,7-diene-7-carboxylate (11b).** Amounts: 700 mg (2.18 mmol) of cyclobutadiene 1, 480 mg (2.18 mmol) of 3.5-di-*tert*-butyl-1,2-benzoquinone (**10b**). Reaction time: 10 min. The greenish yellow oily residue consists of the isomers **13** and **12b** (according to ^1H NMR spectroscopy); **12b** completely isomerizes to **11b** after standing at room temperature for 3 days. The crystalline mass is taken up in 2 mL of petroleum ether (30–75 °C) and suction filtered to give 300 mg (25%) of **11b** as colorless crystals with mp 155 °C: IR (KBr) 1729, 1622, 1582 cm^{-1}; ^1H NMR ($CDCl_3$) δ 0.99, 1.22 (2 s, 9 H each), 1.33 (s, 18 H), 1.37, 1.42 (2 s, 9 H each), 6.63, 6.91 (2 d, J = 2.4 Hz, 1 H each); ^{13}C NMR ($CD\ cl_3$) δ 27.93, 29.55 (br),[19] 30.40, 30.53, 31.52 [$(H_3C)_3C$], 34.07, 34.28, 34.71, 37.90, 38.17 [$(H_3C)_3C$], 81.71 [$(H_3C)_3CO$], 101.48, 102.32 (C-1, C-6), 113.73, 116.89 (*C*H Ar), 138.50, 139.05 (*C*-*t*-Bu Ar), 138.79 (C-7), 142.97, 144.34 (C-3, C-4), 165.46 (C-8), 165.55 (CO ester). Anal. Calcd for $C_{35}H_{56}O_4$: C, 77.73; H, 10.44. Found: C, 78.1; H, 10.42.

***tert*-Butyl 1,6,8-Tri-*tert*-butyl-3,4-(2,4-*tert*-butylbenzo)-2,5-dioxabicyclo[4.2.0]octa-3,7-diene-7-carboxylate (13).** The mother liquor of **11b** from the above procedure is concentrated and the remaining pale yellow oil is chromatographed on 30 g of kiesel gel (Macherey and Nagel, 0.06–0.2 mm; column, 50 × 1 cm) with 250 mL of 4/1 hexane/ether to give 500 mg (42%) of colorless, not completely analytically pure, oily **13**: IR (Film) 1715, 1628, 1609, 1582 cm^{-1}; ^1H NMR ($CDCl_3$) δ 0.97 (s, 9 H), 1.27 (s, 18 H), 1.30, 1.38, 1.48 (3 s, 9 H each), 6.70, 6.88 (2 d, J = 2.4 Hz, 1 H each); ^{13}C NMR NMR ($CDCl_3$) δ 14.10, 22.70,[20] 27.01, 28.08, 29.83, 31.10, 31.66 [$(H_3C)_3C$], 34.27, 34.38, 35.01, 37.40, 38.40 [$(H_3C)_3C$], 81.69 [$(H_3C)_3CO$], 102.25, 103.00 (C-1, C-6), 114.52, 117.33 (*C*H Ar), 136.38, 140.45, 142.83, 143.19, 143.83 (C Ar, C-7), 163.60 (C-8), 166.39 (CO ester).

***tert*-Butyl 1,6,8-Tri-*tert*-butyl-3,4-(1,2-naphtho)-2,5-dioxabicyclo[4.2.0]octa-3,7-diene-7-carboxylate (11c).** Amounts: 640 mg (2.00 mmol) of cyclobutadiene 1, 316 mg (2.00 mmol) of 1,2-naphthoquinone (**10c**). Reaction time: 90 min. The yellow oily residue is treated with 2 mL of petroleum ether (30–75 °C) whereupon crystallization begins. Suction filtration and washing with petroleum ether (30–75 °C) gives 260 mg (27%) of **11c** as colorless crystals with mp 117 °C: IR (KBr) 1712, 1638, 1603 cm^{-1}; ^1H NMR ($CDCl_3$) δ 0.83, 1.28, 1.33 (3 s, 9 H each), 1.47 (br s, 9 H), 7.12–8.06 (m, 6 H); ^{13}C NMR ($CDCl_3$) δ 27.49, 29.10 (br),[19] 30.16 [$(H_3C)_3C$], 34.26, 37.53, 38.60 [$(H_3C)_3C$], 81.81 [$(H_3C)_3CO$], 101.89, 105.80 (C-1, C-6), 120.09–141.03 (C Ar), 141.68 (C-7), 159.17 (C-8), 166-16 (CO ester); MS, *m/e* 478 (5%, M^+), 320 (6%, M^+ – **10c**), 264 (6%, M^+ – **10c** – C_4H_8), 208 (26%, M^+ – **10c** – $2C_4H_8$), 207 [15%, $(H_9C_4)_3C_3^+$], 195 [24%, $(H_9C_4)_2C_3COOH^+$]. Anal. Calcd for $C_{31}H_{42}O_4$: C, 77.79; H, 8.84. Found: C, 77.8; H, 8.84.

***tert*-Butyl 1,6,8-Tri-*tert*-butyl-3,4-(tetrabromobenzo)-2,5-dioxabicyclo[4.2.0]octa-3,7-diene-7-carboxylate (11d).** Amounts: 700 mg (2.18 mmol) of cyclobutadiene 1, 923 mg (2.18 mmol) of tetrabromo-*o*-benzoquinone (**10d**). Reaction time 3 min. The crystalline residue is treated with 2 mL of petroleum ether (30–75 °C), suction filtered, and then washed with cold petroleum ether (30–75 °C) to give 750 mg (46%) of **11d** as colorless crystals with mp 162 °C: IR (KBr) 1712, 1643, 1549 cm^{-1}; ^1H NMR ($CDCl_3$) δ 1.18, 1.34, 1.39, 1.40 (4 s, 9 H each); ^{13}C NMR ($CDCl_3$) δ 28.40, 29.03 (br),[19] 30.03 [$(H_3C_3C$], 34.75, 37.39, 38.91 [$(H_3C)_3C$], 82.96 [$(H_3C)_3CO$], 100.55, 107.28 (C-1, C-6), 114.45, 115.67, 119.57, 120.46 (C Ar), 142.19, 143.31 (C-3, C-4), 142.75 (C-7), 157.88 (C-8), 165.44 (CO ester). Anal. Calcd for $C_{27}H_{36}Br_4O_4$: C, 43.58; H, 4.88. Found: C, 43.8, H, 4.82.

***tert*-Butyl 1,6,8-Tri-*tert*-butyl-3,4-(tetrachlorobenzo)-2,5-dioxabicyclo[4.2.0]octa-3,7-diene-7-carboxylate (11e).** Amounts: 640 mg (2.00 mmol) of cyclobutadiene 1, 491 mg (2.00 mmol) of tetrachloro-*o*-quinone (**10e**). Reaction time: 5 min. The crystalline residue is treated with 2 mL of petroleum ether, suction filtered, and then washed with cold petroleum ether (30–75 °C) to give 500 mg (44%) of **11e** as colorless crystals with mp 161 °C: IR (KBr) 1715, 1645, 1568 cm^{-1}; ^1H NMR ($CDCl_3$) δ 1.16, 1.33, 1.37, 1.40 (4 s, 9 H each); ^{13}C NMR ($CDCl_3$) δ 27.50, 28.50 (br),[19] 29.80 [$(H_3C)_3C$], 34.74, 37.36, 39.01 [$(H_3C)_3C$], 82.84 [$(H_3C)_3CO$], 100.29, 107.35 (C-1, C-6), 120.92, 121.93, 124.54, 125.31 (C Ar), 140.55, 141.86 (C-3, C-4), 142.47 (C-7), 157.39 (C-8), 165.20 (CO ester); MS, *m/e* 566 (<1%, M^+), 208 (13%, M^+ – **10e** – $2C_4H_8$), 207 [40%, $(H_9C_4)_3C_3^+$], 195 [51%, $(H_9C_4)_2C_3COOH^+$]. Anal. Calcd for $C_{27}H_{36}Cl_4O_4$: C, 57.26: H, 6.41. Found: C, 57.1; H, 6.32.

Spiro[5-(*tert*-butoxycarbonyl)-1,2,6-tri-*tert*-butyl-3-oxatricyclo[3.1.0.0.^{2,6}]hexane-4,9′-9′,10′-dihydro-10-oxophenanthrene] (12a). The reaction of 1 with **10a** is carried out as described above with the exception that the reaction is stopped after 2 min, i.e., before the brown suspension has lost its color. Unreacted **10a** is filtered off, the residue is concentrated in vacuum, and the residual oil treated with 2 mL of petroleum ether (30–75 °C) whereupon crystallization begins. Suction filtration and washing with cold petroleum ether (30–75 °C) gives 50 mg (5%) of **12a** as colorless crystals with mp 128 °C: IR (KBr) 1718, 1686, 1600 cm^{-1}; ^1H NMR ($CDCl_3$) δ 0.87, 1.33, 1.35 (3 s, 9 H each), 1.50 (br s, 9 H), 7.33–7.73 (m, 8 H); ^{13}C NMR ($CDCl_3$) δ 27.29, 30.47, 33.45, 33.87 [$(H_3C)_3C$], 26.69, 30.62, 30.94, 32.02,[21] [$(H_3C)_3C$], 48.48, 49.27 (C-1, C-6), 64.82 (C-5), 78.91 (C-4), 81.82 [$(H_3C)_3CO$], 91.98 (C-2), 121.44–140.11 (C Ar), 166.66 (CO ester), 200.20 (CO-10′). Anal. Calcd for $C_{35}H_{44}O_4$: C, 79.51; H, 8.39. Found: C, 79.5; H, 8.39.

X-ray Analysis of 11a. Crystal data: Orthorhombic space group *Pbca*; a = 15.412 (1) Å, b = 19.045 (4) Å, c = 20.835 (3) Å; eight molecules per unit cell; D_{calcd} = 1.148 g cm^{-3}. Data collection: Enraf-Nonius-CAD 4 diffractometer, monochromatized Mo Kα radiation, crystal size 0.55 × 0.40 × 0.25 mm. In the range $2 \leq \theta \leq 23°$, 4239 unique reflections ($+h$, $+k$, $+l$) were measured. Scan width (0.85 + 0.35 tan θ)°, scan speed 1.54–5.0 deg min^{-1}. The average intensity loss of three monotoring reflections (339, $\bar{9}0\bar{2}$, 4 10 $\bar{1}$) was 4.9% which was corrected linearly. Structure solution and refinement: the phase problem was solved with MULTAN 82. Hydrogen atoms (except of H29C and H31A) were located in a ΔF map. The heavy atoms were refined anisotropically, the H atoms isotropically. Full-matrix refinement (3159 reflections with $I > 2\sigma(I)$, unit weights) converged at R = 0.0558, R_w = 0.0542.

(19) This phenonemon in which only one broadened signal is observed for two *tert*-butyl groups is found for all the dihydrodioxins 11 and is presumably the results of hindered rotation of two neighborhing *tert*-butyl substituents.

(20) These two signals result from an impurity.

The largest shift/error ratio was 3.82 for y of C-29, 3.77 for z of C-31, 0.56 for other heavy atoms, and 1.80 for H atoms at this point. Final coordinates, temperature factors, and bond geometry tables are found in the Supplementary Material. All calculations were done with the Enraf-Nonius SDP package on a PDP 11/23 plus computer.

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Registry No. **1**, 83747-03-9; **10a**, 84-11-7; **10b**, 3383-21-9; **10c**, 524-42-5; **10d**, 2435-54-3; **10e**, 2435-53-2; **11a**, 97732-96-2; **11b**, 97732-97-3; **11c**, 97732-98-4; **11d**, 97732-99-5; **11e**, 97733-00-1; **12a**, 97733-01-2; **12b**, 97733-02-3; **13**, 97733-03-4.

Supplementary Material Available: Tables of positional and thermal parameters of **11a**, bond distances and angles, and observed and calculated structure factors (24 pages). Ordering information is given on any current masthead page.

(21) An additional signal is presumably due to the hindered rotation of one *tert*-butyl group; similar phenomena have been observed for the tricyclic systems described in ref 1.

Oxonium Ion Electrophiles: Synthesis of the Hypotensive Oudenone

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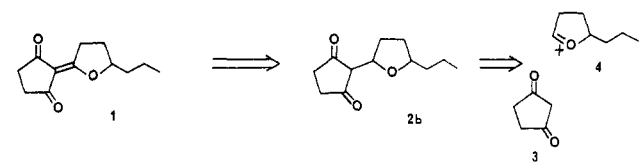
The hypotensive oudenone (**1**) has been synthesized through the intermediacy of oxonium ion **4**. Acid-catalyzed C-alkylation of 1,3-cyclopentanedione (**3**) with 5-propyltetrahydro-2-furanol (**6b**) afforded dihydrooudenone **2b**. In contrast, alkylation of **3** with 2-chloro-5-propyltetrahydrofuran (**7b**) was unsuccessful. Unsaturation was introduced into **2b** by treatment with *N*-(phenylthio)succinimide to produce **10** followed by oxidation to the corresponding sulfoxide and elimination of phenylsulfenic acid, which produced oudenone (**1**).

The hypotensive oudenone (**1**) was isolated[1] from the culture filtrate of the mushroom *Oudemansiella radicata* during an extensive examination[2] of microbial metabolites for enzyme inhibiting activity. The structure and synthesis of oudenone were reported soon thereafter.[3] The hypotensive effect of oudenone, which has been demonstrated in spontaneously hypertensive rats,[4] is caused by epinephrine biosynthesis blockade due to inhibition of tyrosine hydroxylase.[1,5] Oudenone was synthesized from 2-acetyl-1,3-cyclopentanedione in conjunction with structure elucidation,[3,6,7] and one subsequent synthesis has been reported.[8]

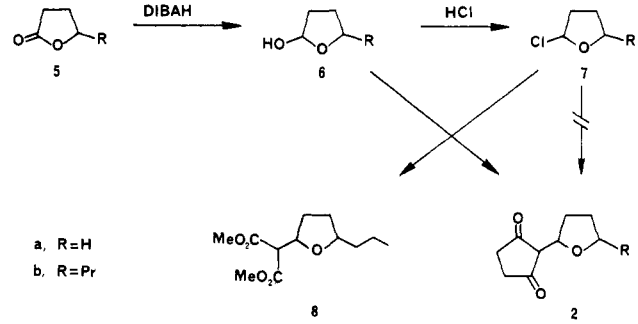
We envisioned that oudenone (**1**) might be synthesized from 1,3-cyclopentanedione (**3**) by C-alkylation with oxonium ion **4** or an equivalent species to afford **2b**, followed by introduction of unsaturation, as depicted in Scheme I. Our previous experience with α-halo ethers[9] and oxonium ions[10] suggested that this approach would be straightforward.

Scheme I



Results and Discussion

Tetrahydro-2-furanol (**6a**), which was utilized in model studies, has previously been prepared in various ways, the most popular of which is reduction of the corresponding lactone (**5a**) with DIBAH.[11] We found that **6a** was prepared more efficiently by acid-catalyzed hydration of 2,3-dihydrofuran.[12]



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