Photochemistry of Epoxyquinones. 2. Photoinduced Cycloaddition Reactions of Aryl- or Alkyl-Substituted 2,3-Epoxy-2,3-dihydro-1,4-naphthoquinones with Olefins[1]

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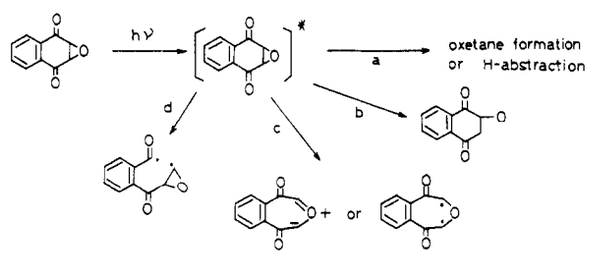
The photochemical reaction of aryl- or alkyl-substituted 2,3-epoxy-2,3-dihydro-1,4-naphthoquinones **1–6** with olefins was examined. Two different photocycloadditions controlled by the substitution pattern of 2,3-substituents have been found. In the photochemical reactions of epoxyquinones **1** and **2** with norbornene, spirooxetanes **7a,b** and **8a,b** were obtained without ring opening of the oxirane. On the other hand, in the photolysis of epoxyquinones **3–6** with norbornene or *N*-phenylmaleimide, cycloaddition the 1,3-dipolar type occurred as a result of the internal C-2–C-3 bond fission of epoxyquinones. Upon further irradiation, the photoadducts undergo novel photoisomerization to yield spirophthalides **17–19** involving the 5-oxabicyclo[2.1.1]hexane system and alkylidene phthalides **13–16.** The distribution of products depends on the length of irradiation and wavelength of the light source. Substituent effects on these reactions and regioselectivity of the cycloadditions are discussed. A tentative mechanism for these novel photoisomerizations is proposed.

Epoxyquinones characterized as "epoxy diones" have potential value as starting materials for the synthesis of useful organic compounds.[2] The photochemistry of oxiranes,[3] α,β-epoxy ketones,[4] and β,γ-epoxy ketones[5] has been well studied. Surprisingly, no systematic study of the photochemistry of epoxyquinones has been reported so far. As shown in Scheme I, the excited epoxyquinones, especially epoxynaphthoquinones, are capable of the following four types of reactions: (a) oxetane formation or hydrogen abstraction from the $n \rightarrow \pi^*$ excited state of the carbonyl group; (b) C–O bond fission of the oxirane ring; (c) C–C bond fission of the oxirane ring and formation of 1,3-dipoles (carbonyl ylides) or 1,3-diradicals; (d) α cleavage (Norrish Type-I). In this paper the photochemical behavior of six epoxyquinones (**1–6**) in the cycloaddition reactions with some suitable olefins, mostly with norbornene and *N*-phenylmaleimide, will be described.

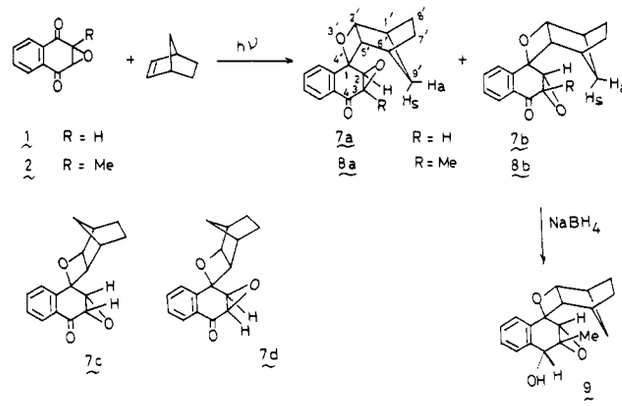
Scheme I



Results and Discussion

Photocycloaddition Reactions of Epoxyquinones 1 and 2 with Norbornene. Irradiation of a benzene solution of 2,3-epoxy-2,3-dihydro-1,4-naphthoquinone (**1**) (0.016 M) and norbornene (0.18 M) by means of a 300-W high-pressure mercury lamp in a Pyrex tube for 30 h gave two stereoisomeric 1:1 adducts **7a** and **7b** in 60% yield (**7a/7b** = 1:1.4 estimated by NMR; Scheme II). Two adducts **7a** and **7b** were separated by preparative TLC. The structures of these adducts were assigned as 2,3-epoxy-4-oxo-1,2,3,4-tetrahydronaphthalene-1-spiro-4′-(3′-oxatricyclo[4.2.1.$0^{2',5'}$]nonane) on the basis of spectral data outlined below. The IR spectra of **7a** and **7b** showed one carbonyl band at 1690 cm^{-1}, as well as characteristic bands at 880 and 850 cm^{-1} due to the oxirane ring. The NMR spectrum of **7a** similar to that of **7b** showed three doublets at δ 3.73, 4.36, and 4.96 due to the protons H-3, H-2, and H-2′, respectively. The configurations of spirooxetanes **7a** and **7b** were assigned on the basis of their NMR spectra. Absence of coupling of protons H-2′ and H-5′ with the bridgehead

Scheme II



protons H-1′ and H-6′ indicated that the protons H-2′ and H-5′ occupied the endo positions to the norbornyl ring.[6] In the NMR spectrum of **7a,** the bridgehead protons H-1′ and H-6′ (appearing at δ 2.37 and 3.12, respectively) and methylene bridge protons H_a-9′ and H_s-9′ (appearing at δ 1.56 and 2.56, respectively) are in very different environments, while in the other isomer **7b** the two bridgehead protons at δ 2.46 have the same chemical shifts (see Experimental Section). Such outstanding differences in the chemical shifts of the bridgehead protons and methylene bridge protons in **7a** are explicable in terms of the proximity effect of one bridgehead proton H-6′ and syn methylene bridge protons H_s-9′ to the oxygen atom of the oxirane ring in **7a,** confirmed with a molecular model. The deshielding effect of the oxygen atom shifts H-6′ and H_s-9′ of **7a** downfield,[7] while none of bridgehead protons in **7b** are affected by the oxygen atom of the oxirane ring. In addition to **7a** and **7b,** two other possible stereoisomers **4c** and **4d** might be formed. However, molecular models show that the methylene bridge in **7c** and **7d** is severely hindered by the fused aromatic ring. Accordingly, it is unlikely to result in the reaction. Furthermore, structures **7c** and **7d** are incompatible with the observed NMR spectra.

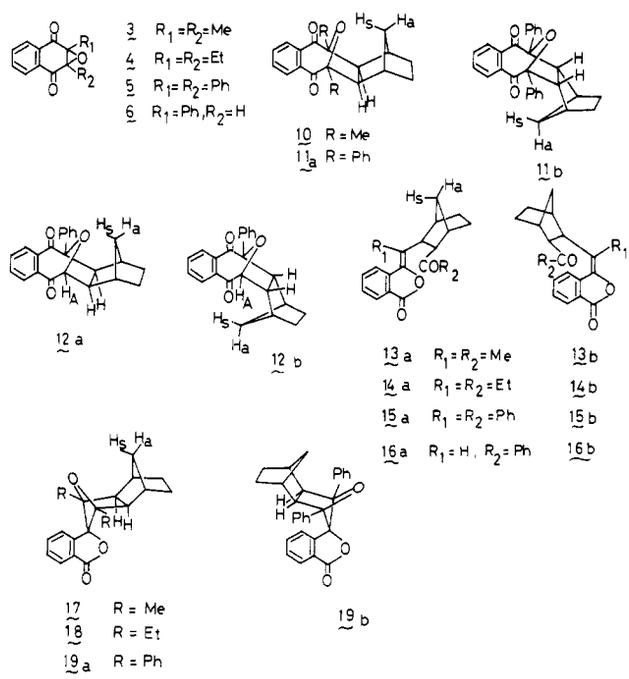
Irradiation of 2-methyl-2,3-epoxy-2,3-dihydro-1,4-naphthoquinone (**2**) with norbornene also gave a mixture of nearly equal amounts of the two stereoisomeric oxetanes **8a** and **8b** (86%). The configurations of **8a** and **8b** were assigned by comparing their NMR spectra with those of **7a** and **7b.** The unsymmetrical epoxyquinone **2** has two different carbonyl groups. In order to determine which carbonyl group added to norbornene, the isomer **8b** was converted into the alcohol **9** by reduction with sodium borohydride, whose NMR spectrum

Table I. Photochemical Reactions of Epoxyquinones 3–6 with Norbornene

Entry	Epoxyquinone[f]	Time, h	Condition[a]	Product (%)[b] Primary adduct	Alkylidene phthalide	Spirophthalide
1	3	5	Pyrex[c]	10 (8)	13a (11) 13b (8)	17 (65)
2	3	100	Quartz[d]		13a (47) 13b (45)	
3	4	10	Pyrex		14a (10) 14b (10)	18 (57)
4	4	20	Quartz		14a (59) 14b (38)	
5	5	5	>340 nm	11a (15) 11b (35)	15a (26) 15b (8)	19a (13) 19b (tr)
6	5	20	>340 nm		15a (6) 15b (15)	19a (41) 19b (29)
7	5	30	254 nm[e]		15a (34) 15b (40)	
8	6	7.5	>340 nm	12a (45) 12b (14)	16a (11) 16b (7)	
9	6	50	Quartz	12a (22)	16a (43) 16b (33)	

[a] Irradiation was carried out using a 300-W high-pressure mercury lamp or 120-W low-pressure mercury lamp. [b] Yields of products were based on epoxyquinones used. [c] λ >290 nm. [d] λ >200 nm. [e] A 120-W low-pressure mercury lamp was used. [f] Registry no.: **3**, 53948-58-6; **4**, 63688-80-2; **5**, 54328-51-7; **6**, 13369-47-6.

Chart I



showed the proton H-2 at δ 3.79 as a sharp singlet, suggesting the addition of the carbonyl group at C-4 of **2** to norbornene. Thus, in the photochemical reaction of **2** with norbornene it was concluded that cycloaddition of norbornene to **2** occurred selectively on the carbonyl group at C-4.

From these data, for epoxyquinones **1** and **2**, intermolecular oxetane formation from the n → π* excited state (presumably triplet state)[8] (type a in Scheme I) is predominant rather than C–O bond fission or C–C bond fission of the oxirane ring. Furthermore, in the case of the unsymmetrical epoxyquinone **2**, cycloaddition occurred on the less hindered carbonyl group at C-4.

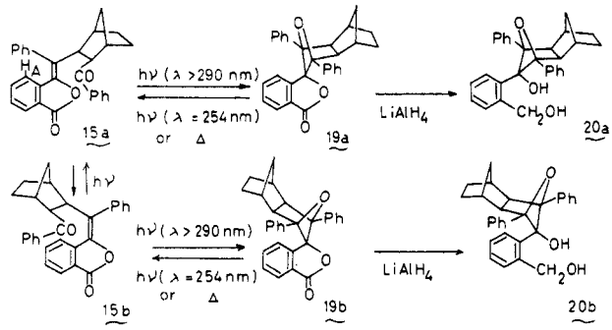
Photocycloaddition Reactions of Epoxyquinones 3–6 with Norbornene, Norbornadiene, and Electron-Deficient Olefins. Irradiation of epoxyquinones **3–6** in the presence of norbornene gave no oxetanes, but three types of products; i.e., 1,3-dipolar cycloaddition type 1:1 adducts (**10–12**), alkylidene phthalides (**13–16**), and spirophthalides (**17–19**) were obtained as shown in Chart I. The alkylidene phthalides (**13–16**) and spirophthalides (**17–19**) are undoubtedly the photoisomerization products of the primary adducts **10–12**, because the primary adducts when isolated are readily converted into them upon further irradiation. Therefore, the primary reaction is of the 1,3-dipolar cycloaddition type in the photochemical reaction of epoxyquinones **3–6** with olefins (type c in Scheme I). The results of the photochemical reactions of epoxyquinones **3–6** with norbornene under several different conditions are summarized in Table I. In Table I, the most striking point is that the distribution of products depends on the length of irradiation and wavelength of the light source, particularly in the case of 2,3-diphenyl-2,3-epoxy-2,3-dihydro-1,4-naphthoquinone (**5**). Irradiation (λ >340 nm) of a benzene solution of epoxyquinones **5** and norbornene for 5 h gave two stereoisomeric 1:1 adducts **11a** and **11b** in a combined yield of 50%, while upon longer irradiation (λ >340 nm) for 20 h spirophthalides **19a** (41%) and **19b** (29%) were obtained as the main products (entry 5 and 6). On the other hand, irradiation (λ 254 nm) of **5** and norbornene in acetonitrile using a 120-W low-pressure mercury lamp for 30 h gave (*E*)- and (*Z*)-3-[α-(3-benzoylnorbornan-2-yl)benzylidene]phthalide [**15a** (34%) and **15b** (40%)] as the main products (entry 7). Thus, three types of products could be obtained as the main products in separate experiments by controlling the reaction conditions. These reactions, therefore, are of synthetic as well as mechanistic significance. In the case of 2,3-dimethyl-2,3-epoxy-2,3-dihydro-1,4-naphthoquinone (**3**) and 2,3-diethyl-2,3-epoxy-2,3-dihydro-1,4-naphthoquinone (**4**), it is difficult to isolate the primary photoadducts, as shown in Table I (entry 1 and 3), because the primary photoadducts readily underwent further photoisomerization into spirophthalides (**17** and **18**) and alkylidene phthalides (**13a,b** and **14a,b**). However, by careful workup one can isolate the primary photoadduct **10** in low yield (3%).[9] Actually, upon further irradiation of isolated **10** photoisomerization readily occurred to yield the spirophthalide **17** as a main product, together with small amounts of alkylidene phthalides **13a** and **13b**. In the case of 2-phenyl-2,3-epoxy-2,3-dihydro-1,4-naphthoquinone (**6**) no spirophthalide was formed, presumably because of its thermal or photochemical transformation to alkylidene phthalides **16a** and **16b**.

In addition, the photointerconversion between alkylidene phthalides **15a,b** and spirophthalides **19a,b**, as shown in Scheme III, makes the reacting system more complex. Upon irradiation through a Pyrex filter (λ >290 nm), the alkylidene phthalide **15a** or **15b** is converted into a mixture of two stereoisomeric spirophthalides **19a** and **19b**, while irradiation (λ 254 nm) of the spirophthalide **19a** or **19b** in acetonitrile using a 120-W low-pressure mercury lamp gave a mixture of two isomeric alkylidene phthalides **15a** and **15b** (Table II). The photoconversion of **15a** and **15b** to **19a** and **19b** can be explained in terms of an intramolecular Paterno–Büchi reaction.[11] On the other hand, irradiation (λ >254 nm) of **19a** or **19b** gave an equilibrating mixture of **15a** and **15b** (Table II). Photoconversion from the spirophthalides **17** and **18** to alkylidene phthalides **13a,b** and **14a,b** similarly occurred,

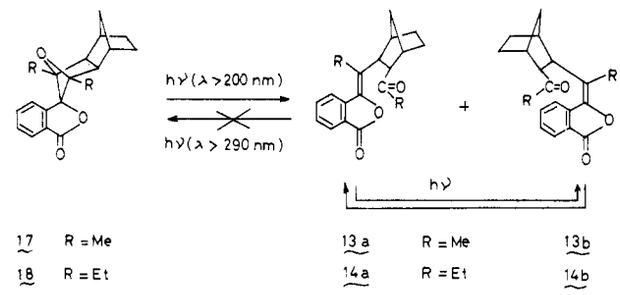
Table II. Photointerconversion between Alkylidene Phthalides 15a,b and Spirophthalides 19a,b

Starting	Registry no.	Condition, nm	Solvent	Product, % 15a	15b	19a	19b
15a	63688-81-3	>290	C_6H_6			22	71
15b		>290	C_6H_6			31	61
19a	63688-82-4	254	CH_3Cl	34	44		
19b	63729-73-7	254	CH_3CN	33	46		

Scheme III



Scheme IV



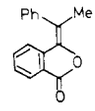
whereas the reverse reaction, i.e., intramolecular oxetane formation, was not observed (Scheme IV).

Structural analysis of the photoproducts rests on the physical and chemical data outlined below. The NMR data of the products derived from the photolysis of **3–6** with norbornene are summarized in Table III. For the primary adducts **11a** and **11b,** each IR spectrum showed a single carbonyl band at 1690 cm^{-1}. The NMR spectrum showed the presence of a symmetry plane. Therefore, these compounds were 1,3-dipolar cycloaddition type adducts. The configurations of **11a** and **11b** were assigned on the basis of their NMR spectra. Methine protons H-2 and H-3 in **11a** and **11b** are minimally coupled to the 1,4-bridgehead protons, as predicted by the Karplus relation for endo protons, but weakly coupled to the anti bridge proton H_a-7 (J = 1.3 Hz, W rule), leading to the conclusion that protons H-2 and H-3 in **11a** and **11b** occupy endo positions to the norbornyl ring.[7] Molecular models show that in the endo adduct **11b** the syn methylene bridge proton (H_s-7) and the 1,4-bridgehead protons (H-1 and H-4) lie over the aromatic ring and carbonyl groups, respectively, whose anisotropic shielding effect makes these signals shift to higher field relative to those of the exo adduct **11a** (Chart I, Table III).[10] Furthermore, methine protons H-2 and H-3 of **11b** (appearing at δ 2.94) are deshielded relative to those of **11a** (appearing at δ 2.75) by the anisotropy of the proximal oxygen bridge.[7] Therefore, the two adducts **11a** and **11b** are concluded to be exo,exo adduct and endo,exo adduct, respectively. As shown in Table I, the endo,exo adduct **11b** was formed in preference to the exo,exo adduct **11a** in the photochemical reaction of **5** with norbornene. For the primary adduct **12a** derived from the photolysis of **6** with norbornene, the exo,exo configuration was assigned on the basis of its NMR spectrum.

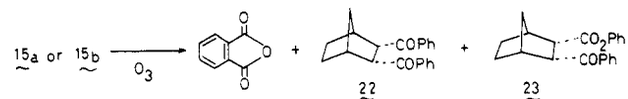
The NMR spectrum showed J = 2 Hz between H_A and H-3, in agreement with a dihedral angle of approximately 105° predicted from examination of a molecular model.[12] Furthermore, the chemical shifts of methylene bridge protons (H_a-7 and H_s-7) of **12a** are closer to those in the exo,exo adduct **11a** than in those of endo,exo adduct **11b** (Table III).

The primary adduct **10** was also assigned as the exo,exo adduct by comparing its NMR spectrum with that of **11a** or **11b.** Thus, in the photochemical reaction of epoxyquinones **3** and **6** with norbornene exo,endo adducts were preferentially formed, in contrast to the case of epoxyquinone **5.**

For the alkylidene phthalides **15a** and **15b,** their IR spectra showed three characteristic bands at ca. 1770 (five-membered lactone C=O), 1670 (phenyl C=O), and 1640 (C=C) cm^{-1}. The NMR spectra showed two doublets at δ ~3.8 and 4.2 due to the protons H-2 and H-3. UV spectra exhibited characteristic absorption at 323 nm (ϵ ~9000) attributed to the alkylidene phthalide moiety, supported by similar absorption at 320 nm (ϵ 11 000) in the analogous phthalide **21.**[13] These spectral data are in agreement with alkylidene phthalide structures. The NMR spectrum of **15a** showed a shielded one-proton signal at δ 5.78 due to the aromatic proton H_A (Scheme III) which lay over the phenyl ring. The phthalide **21** similarly showed a characteristic NMR signal at δ 6.6.

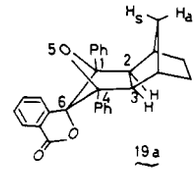


21



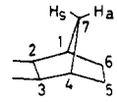
Therefore, the configurations of **15a** and **15b** were concluded to be E and Z, respectively. Structures **15a** and **15b** were substantiated by ozonolysis of **15a** and **15b,** which gave phthalic anhydrides 2α,3α-dibenzoylnorbornane (**22**) and 2α-phenoxycarbonyl-3α-benzoylnorbornane (**23**), respectively. For the other alkylidene phthalides (**13a,b, 14a,b,** and **16a,b**), structures were confirmed by spectral data, and configurations were assigned on the basis of the respective NMR spectra.[13]

For the spirophthalides **19a** and **19b,** IR and UV spectra resemble those of phthalide: i.e., **19a** [IR (KBr) 1755 cm^{-1} (lactone C=O); UV ($CHCl_3$) λ_{max} 283, 286 nm (ϵ 3300 and 3400)]; **19b** [IR (KBr) 1755 cm^{-1} (C=O); UV ($CHCl_3$) λ_{max} 288 nm (ϵ 3800)]; phthalide (IR (KBr) 1758 cm^{-1} (C=O), UV ($CHCl_3$) λ_{max} 277, 281 nm (ϵ 1900 and 2000)]. The highly symmetrical structures of **19a** and **19b** were suggested by the presence of two equivalent methine protons at δ 3.00 (s) and 3.11 (s), respectively, as well as two equivalent 1,4-bridgehead



19a

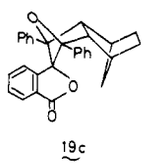
Table III. NMR Spectral Data[a] of Products Derived from the Photochemical Reactions of Epoxyquinones 3–6 with Norbornene



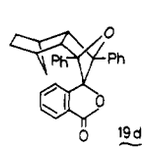
Registry no.	Product	Chemical shift,[b] δ (J, Hz) H-1 and H-4	H-2 and H-3	H-7	H-5 and H-6 aromatic-H others
57188-27-9	10	2.46 (br s, 2 H)	2.35 (s, 2 H)	0.50 (d, H_a, J = 10) 0.96 (d, H_s, J = 10)	1.0–1.7 (m, 4 H) 1.59 (s, 6 H, CH_3) 7.5–7.84 (m, 4 H)
63688-83-5	11a	2.96 (br s, 2 H)	2.75 (d, 2 H, $J_{2,7a}$ = 1.3)	0.73 (d, H_a, J = 12) 1.13 (d, H_s, J = 12)	1.0–1.8 (m, 4 H) 7.0–7.63 (m, 14 H)
63729-74-8	11b	2.05 (br s, 2 H)	2.94 (d, 2 H, $J_{2,7a}$ = 1.3)	0.45 (d, H_s, J = 10) 1.09 (d, H_a, J = 10)	1.2–1.5 (m, 4 H) 7.0–7.8 (m, 14 H)
63688-84-6	12a	1.98 (br s, 1 H) 2.50 (br s, 1 H)	2.86 (d, H-2, J = 9) 2.48 (dd, H-3)	0.09 (d, H_a, J = 11) ~1.2 (d, H_s)	1.0–1.5 (m, 4 H) 4.64 (d, H_a, J = 2) 7.0–7.8 (m, 9 H)
	15a	2.27 (br s, 1 H) 2.47 (br s, 1 H)	3.75 (d, 1 H, J = 9) 4.22 (d, 1 H, J = 9)	1.03 (d, H_a, J = 10) 1.80 (d, H_s, J = 10)	1.1–1.7 (m, 4 H) 5.78 (dd, H_a, J = 8.2) 7.0–8.0 (m, 13 H)
	15b	2.50 (br s, 2 H)	3.80 (d, 1 H, J = 9) 4.12 (d, 1 H, J = 9)	0.98 (d, H_a, J = 10) 1.70 (d, H_s, J = 10)	1.2–1.8 (m, 4 H) 6.8–8.1 (m, 14 H)
	19a	2.24 (br s, 2 H)	3.00 (s, 2 H)	0.92 (d, H_a, J = 10) 2.77 (d, H_s, J = 10)	1.2–1.6 (m, 4 H) 7.2–7.8 (m, 14 H)
	19b	2.42 (br s, 2 H)	3.11 (s, 2 H)	0.96 (d, H_a, J = 10) 2.87 (d, H_s, J = 10)	1.2–1.8 (m, 4 H) 7.1–8.1 (m, 14 H)
63688-85-7	17	2.38 (br s, 2 H)	2.32 (s, 2 H)	0.91 (d, H_a, J = 9) 2.42 (d, H_s)	1.0–1.6 (m, 4 H) 1.17 (s, 6 H, CH_3) 7.4–8.0 (m, 4 H)
63688-86-8	18	2.45 (br s, 2 H)	2.56 (s, 2 H)	0.94 (d, H_a, J = 10) ~2.50 (H_s)	0.62 (t, 6 H, CH_3) 1.10–1.96 (m, 8 H) 7.6–8.21 (m, 4 H)

[a] Spectra were determined with a JEOL PS-100 (100 MHz). [b] Chemical shifts relative to Me_4Si in $CDCl_3$, s = singlet, d = doublet, t = triplet, m = multiplet, br s = broad singlet, dd = doublet of doublet.

protons at δ 2.44 (br s) and 2.42 (br s), respectively (Table III). The downfield shifts of the syn bridged methylene proton signals (H_s-7) of **19a** and **19b** at δ 2.77 (d) and 2.87 (d), compared to those of the anti methylene proton (Ha-7) at δ 0.92 (d) and 0.96 (d), were attributed to the anisotropic deshielding effect of the oxygen bridge.[7] These spectral data are consistent with the spirophthalide structures **19a** and **19b.** These structures were also supported by reduction of **19a** and **19b** with $LiAlH_4$ to afford the corresponding benzyl alcohols **10a** and **20b,** respectively (Scheme III). The configurations of H-2 and H-3 in **19a** and **19b** are endo to the 5-oxabicyclo[2.1.1]-hexane system, because the other two isomers **19c** and **19d** are

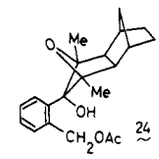


19c



19d

severely hindered and, accordingly, the formation of these isomers is improbable. The configurations of **19a** and **19b** at C-6 in the 5-oxabicyclo[2.1.1]hexane system were unambiguously determined by the following chemical evidence. The pyrolysis of **19a** in refluxing xylene stereospecifically afforded (*E*)-3-[α-(3-benzoylnorbornan-2-yl)benzylidene]phthalide (**15a**), while the pyrolysis of **19b** stereospecifically afforded *Z* isomer **15b** (Scheme III). Therefore, it is concluded that the configurations of the C-6–O bonds of the phthalide moieties in **19a** and **19b** are endo and exo, respectively, to the 5-oxabicyclo[2.1.1]hexane system. For other spirophthalides **17** and **18,** no configurations at C-6 could be determined chemically, because pyrolyses of these spirophthalides are nonstereospecific. Therefore, configurations of these spirophthalides were assigned by comparison of NMR spectra and R_f values



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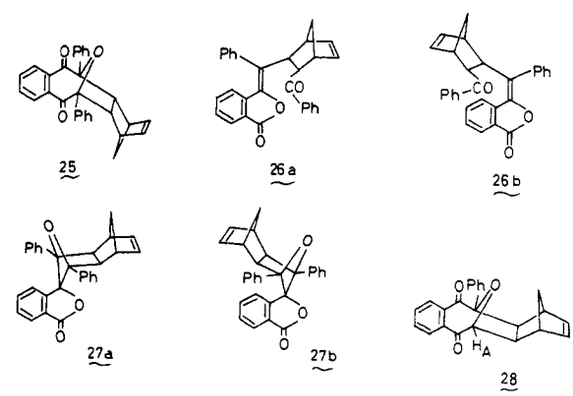
in TLC with those of **19a** and **19b.** Reduction of **17** with $LiAlH_4$ in ether and subsequent acetylation gave compound **24.**

Irradiation of epoxyquinone **5** with norbornadiene gave the similar photoproducts **25–28** (Chart II). In this case, the primary photoadducts derived from the photolysis of **5** and **6** with norbornadiene were exclusively endo,exo adduct **25**[14] and exo,exo adduct **28,** respectively, whose configurations were assigned by comparing their NMR spectra with those of the analogous adducts **11a,b** and **12a.**

We have also investigated photocycloaddition reactions of

Chart II



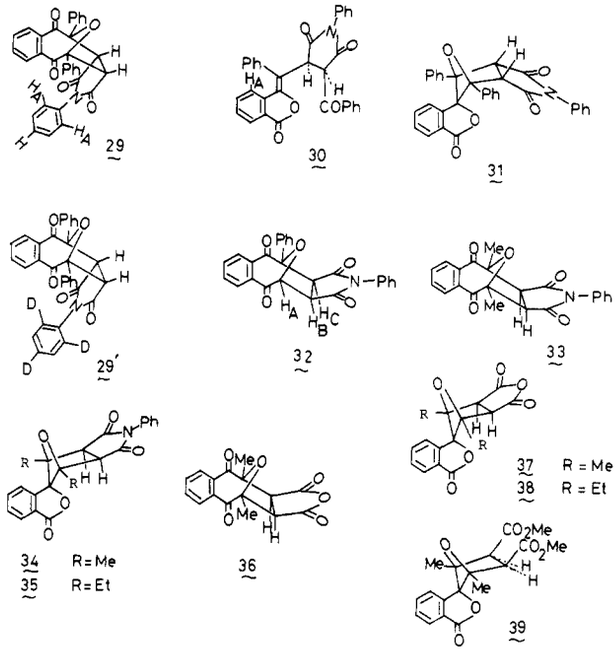
25 26a 26b 27a 27b 28

Table IV. NMR Spectral Data of Products Derived from the Photochemical Reactions of Epoxyquinones 3–6 with *N*-Phenylmaleimide

Registry no.	Product	Chemical shift, δ (*J*, Hz) Methine H	Aromatic H, others
54485-97-1	**29**	4.33 (s, 2 H)[a]	6.50 (m, 2 H, H_A) 7.1–8.0 (m, 17 H)
63688-87-9	**30**	5.10 and 5.19 (AB q, H_B and H_C, J = 5)[a]	6.45 (dd, H_A) 7.1–7.84 (m, 18 H)
63688-88-0	**31**	4.38 (s, 2 H)[a]	7.1–7.8 (m, 19 H)
63688-89-1	**32**	4.16 (dd, H_B, J = 2, 9)[b] 4.35 (d, H_C, J = 9) 5.51 (d, H_A, J = 2)	6.9–7.9 (m, 14 H)
63729-75-9	**33**	3.87 (s, 2 H)[b]	1.56 (s, 6 H, CH_3) 7.2–8.9 (m, 9 H)
63688-90-4	**34**	3.77 (s, 2 H)[b]	1.39 (s, 6 H, CH_3) 17.13–8.07 (m, 9 H)
63688-91-5	**35**	3.96 (s, 2 H)[a]	0.73 (t, 3 H, CH_3) 1.98 (m, 2 H, CH_2) 7.13–8.14 (m, 9 H)

[a] Solvent: $CDCl_3$. [b] Solvent: CD_3SOCD_3.

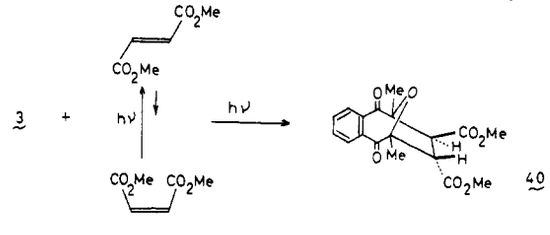
Chart III



epoxyquinones **3–6** with electron-deficient olefins. Irradiation (λ >340 nm) of a solution of epoxyquinones **3–6** and *N*-phenylmaleimide gave the 1:1 adducts **29–35.** In this case, the distribution of products also depends on the length of irradiation. In the photochemical reaction of epoxyquinone **5** with *N*-phenylmaleimide, the main product was the 1:1 adduct **29** (24%) at 36% conversion of epoxyquinone **5** accompanied by a small amount of (*E*)-3-[α-(phthalidylidenebenzyl)-4-benzoyl]-*N*-phenylsuccimide (**30**). On the other hand, prolonged irradiation (λ >340 nm) of a solution of **5** and *N*-phenylmaleimide in benzene for about 50 h gave the spirophthalide **31** as a main product in 43% yield. The dependence of the product distribution on the length of irradiation is similar to that observed in the photochemical reaction of **5** with norbornene. Products **30** and **31** are secondary reaction products formed by photoisomerization of the primary adduct **29,** because they were formed upon further irradiation of the primary adduct **29.** In the photochemical reaction of epoxyquinone **6** with *N*-phenylmaleimide, at 78% conversion of **6,** a 1:1 adduct **32** was obtained as a main product in 55% yield. In contrast to the photochemical reaction of **5** and **6** with *N*-phenylmaleimide, in the photochemical reaction of epoxyquinone **3** with *N*-phenylmaleimide it is difficult to isolate the primary photoadduct **33** because of its greater photoisomerization tendency to the spirophthalide **34.** In this case, the spirophthalide **34** was obtained in higher yield (76%), together with a small amount of the primary photoadduct **33.**[15] Irradiation of epoxyquinone **3** with maleic anhydride similarly gave spirophthalide **37** in 76% yield, together with a small amount of the primary photoadduct **36.** Irradiation of epoxyquinone **4** with *N*-phenylmaleimide and maleic anhydride also gave spirophthalides **35** and **38** in 58 and 65% yields, respectively.

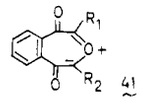
Structural analysis of these photoproducts rests on their NMR, UV, mass, and elemental analyses. The NMR data are summarized in Table IV. The IR spectrum of **29** showed three carbonyl bands at 1777 (w), 1716 (s) (imide C=O), and 1685 (s) (phenyl C=O) cm^{-1}, and the NMR spectrum showed a singlet at δ 4.33 due to two methine protons of the imide moiety, in agreement with the highly symmetrical structure **29.** The NMR spectrum of **29** showed a shielded two-proton signal at δ 6.5 attributed to the aromatic protons H_A which lay over another aromatic ring,[16] confirmed by preparation of the analogous trideuterated compound **29'.**[17] Thus, it is concluded that the configuration of this adduct **29** is endo. For the 1:1 adduct **32,** the NMR spectrum showed a coupling of 2 Hz (J_{AB}), which suggested the exo configuration similar to the case of adduct **12a,** derived from photolysis of epoxyquinone **6** with norbornene. Furthermore, the NMR spectrum of **32** and **33** showed no shielded aromatic proton signal as observed in the NMR spectrum of **29.** Therefore, it is concluded that the configurations of adducts **32** and **33** are exo.[15] For the products **30** and **31,** structures were assigned by comparing their IR, UV, and NMR spectra with those of **15a,b** and **19a,b.** Pyrolysis of **31** in refluxing decalin stereospecifically afforded alkylidene phthalide **30** with *E* configuration. Therefore, it is concluded that the configuration of the C-6–O bond of spirophthalide **31** is endo to the 5-oxabicyclo[2.1.1]hexane system. However, the configurations at C-2, and C-5, remain to be assigned. Irradiation of the isolated alkylidene phthalide **30** gave no spirophthalide **31,** unlike the photochemical conversion of alkylidene phthalides **15a,b** to spirophthalides **19a,b.** On the other hand, irradiation of the primary adduct **29** readily gave the spirophthalide **31.** Therefore, the spirophthalide **31** is not formed by intramolecular oxetane formation of **30,** but by direct photoisomerization of the primary adduct **29.** If the photoisomerization could proceed without inversion of configuration as discussed later, the configuration of the imide moiety of **31** will be same as that of the primary adduct **29.** Thus, we tentatively conclude that the configuration of the imide moiety of **31** is endo to the 5-oxabicyclo[2.1.1]-hexane system. For the same reasons, the configurations of the imide moieties and anhydride moieties of spirophthalides **34–38** were tentatively assigned as exo to the 5-oxabicyclo[2.1.1]hexane system. The spirophthalide **37** was treated with diazomethane to give the symmetrical dimethyl ester **39** in quantitative yield.

Irradiation of benzene solutions of 2,3-dimethyl-2,3-epoxy-2,3-dihydro-1,4-naphthoquinone (**3**) in the presence of excess dimethyl fumarate or dimethyl maleate gave the



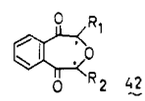
same 1:1 adduct **40** in 52 and 40% yield, respectively: IR (KBr) 1735 (ester), 1695, 1685 (phenyl C=O) cm^{-1}; NMR ($CDCl_3$) δ 1.41 (s, 3 H), 1.70 (s, 3 H), 3.47 (d, 1 H), 3.58 (d, 1 H), 3.65 (s, 3 H), 3.73 (s, 3 H), 7.5–7.98 (m, 4 H). These spectral data are in agreement with structure **40.** Under the conditions, dimethyl fumarate can isomerize to dimethyl maleate in competition with photocycloaddition, while the configuration of dimethyl maleate remains unchanged. Nevertheless, the main cycloadduct was **40** with trans configuration. The adduct **40** was also obtained by treatment of the adduct **36** with diazomethane.

Thus, irradiation of epoxyquinones **3–6** with norbornene gave no oxetanes, but rather gave adducts **10–12** produced via 1,3-dipolar cycloaddition. Formation of adducts **10–12** indicates unambiguously the fission of the internal C-2–C-3 bond of the oxirane ring via the transient carbonyl ylides **41a–d** or 1,3-diradicals **42a–d.** A similar type of cycloaddition reactions



41

a) $R_1 = R_2 = Me$
b) $R_1 = R_2 = Et$
c) $R_1 = R_2 = Ph$
d) $R_1 = Ph$, $R_2 = H$



42

occurred in the photochemical reactions of epoxyquinones **3, 5,** and **6** with electron-deficient olefins such as *N*-phenylmaleimide, maleic anhydride, and dimethyl fumarate. The characteristic feature of the photochemistry of epoxyquinones **3–6** compared with other epoxyquinones **1** and **2** suggests the importance of the following factors: (a) relief of intramolecular strain; (b) stabilization of intermediate carbonyl ylides or 1,3-diradicals; (c) disrotatory ring opening of the oxirane controlled by orbital symmetry. The strain energy of epoxyquinones **1–6** may increase in the order **1 < 2 < 6 < 3 < 4 < 5** because the steric repulsion between 2,3 substituents in epoxyquinones **1–6** may increase in this order. Therefore, in the case of epoxyquinones **3–6** the intramolecular strain is released by the formation of carbonyl ylides or 1,3-diradicals. Stabilization of intermediate carbonyl ylides or 1,3-diradicals can be expected in most of the dialkyl- or diaryl-substituted epoxynaphthoquinones **3–5.** Even in the photolysis of monoaryl-substituted epoxyquinone **6,** aryl-conjugated carbonyl ylide **41d** or 1,3-diradical **42d** can undergo a cycloaddition reaction of 1,3-dipolar type.

Woodward and Hoffmann predicted thermal conrotation and photochemical disrotation for the conversion of cyclopropyl anions into allyl anions.[18] The predictions have been verified in the reactions of the isoelectronic aziridines[19] and oxiranes.[20] When the oxirane ring is constrained in a bicyclic system of medium size (e.g., five- or six-membered ring), distrotation photochemical ring opening is allowed, but thermal conrotatory ring opening is not permitted because of the geometry of the system, with two exceptions.[21,22] In the present photochemical reaction, the orbital symmetry allowed ring openings (disrotatory) were observed, while thermal reaction of epoxyquinone **3** in dimethyl maleate gave no corresponding adduct, supporting the prediction described above.

Although either carbonyl ylides or 1,3-diradicals could be the intermediates here, we cannot distinguish between them. However, carbonyl ylides have been frequently assumed as the intermediates in the photolysis or prrolysis of oxiranes,[23] and some of them were actually identified by spectroscopic evidence.[20-22] Based on estimated frontier orbital energies for the less electron-deficient carbonyl ylides formed from 2,3-dicarbonyl-2,3-diaryl- or -dialkyloxiranes such as **3–6,** Houk has suggested that these ylides will react readily with both

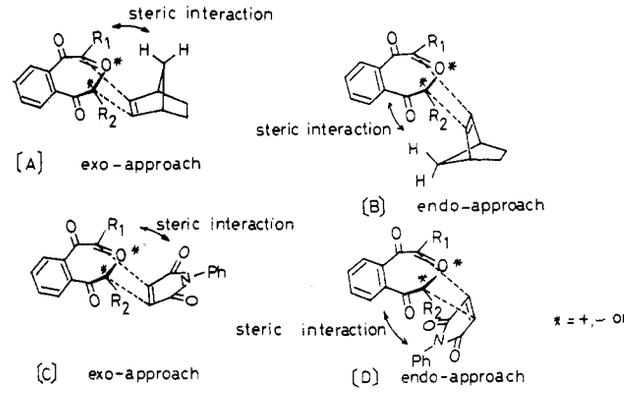


Figure 1.

electron-deficient and electron-rich dipolarophiles.[24] The formation of [3 + 2 → 5] adducts from epoxyquinones **3–6** and electron-defficient olefins such as *N*-phenylmaleimide or electron-rich olefins such as norbornene supports Houk's conclusions and carbonyl ylide intermediates. Recently Lee concluded from the standpoint of the stereospecificity of cycloaddition that the possible intermediate on the direct irradiation of stilbene oxides was the carbonyl ylide, while it was the orthogonal diradical in acetone-sensitized photolysis of stilbene oxides.[25]

In this investigation irradiation of epoxyquinone **3** mixed with dimethyl maleate or with dimethyl fumarate gave the 1:1 adduct with trans configuration regardless of the stereochemistry of the starting olefins. Therefore, the possibility of 1,3-diradical intermediates cannot be ruled out completely, because addition of olefins to 1,3-radical intermediates would produce diradicals capable of free rotation prior to ring closure, while cycloaddition reactions via carbonyl ylides are generally stereospecific.

With regards to the stereochemistry of the primary cycloadducts, endo adducts predominate in the photochemical reactions of the epoxyquinine **5** with norbornene or *N*-phenylmaleimide, while exo adducts predominate in the photochemical reaction of **3** and **6** with norbornene and *N*-phenylmaleimide. The observed orientations can be explained by considering steric interactions between two reactants (van der Waals repulsion) rather than the electronic interactions (π overlap or dipole–dipole interaction), because electronic interactions would be favorable to endo approach in the photocycloaddition reactions of epoxyquinones with *N*-phenylmaleimide (Figure 1D). In the reaction of epoxyquinone **5** exo approach would be unfavorable because of the steric interaction between bulky 2,3-diphenyl substituents and approaching olefins (Figure 1A,C), while in those of epoxyquinones **3** and **6** the lesser steric interaction would be favorable to exo approach rather than endo approach (Figure 1B,D).

The primary photoadducts undergo novel photoisomerizations to give spirophthalides and alkylidene phthalides. The mechanism which explains economically the observed photoisomerization is outlined in Schemes V and VI. A mechanism involving the initial α cleavage of the adducts **11a** (or **11b**), followed by the subsequent intramolecular rearrangement of the resulting radicals **43** (or **45**) to **44** (or **46**), can successfully explain the simultaneous formation of alkylidene phthalides, **15a** plus **15b,** and spirophthalides, **19a** plus **19b.** In **46** cyclization to give **19c** and **19d** may not occur because of the strong internal strain in **19c** and **19d.**

In addition to the photoisomerizations we also found the photointerconversion between alkylidene phthalides **15a,b** and spirophtahlide **19a,b.** The photoconversion of alkylidene phthalides **15a** and **15b** to spirophthalide **19a** and **19b** can be interpreted by stepwise intramolecular oxetane formation[8,11]

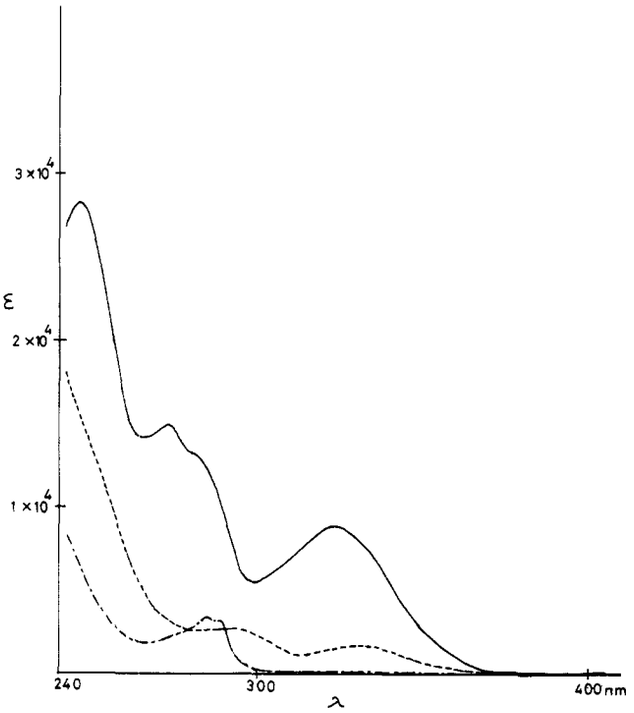
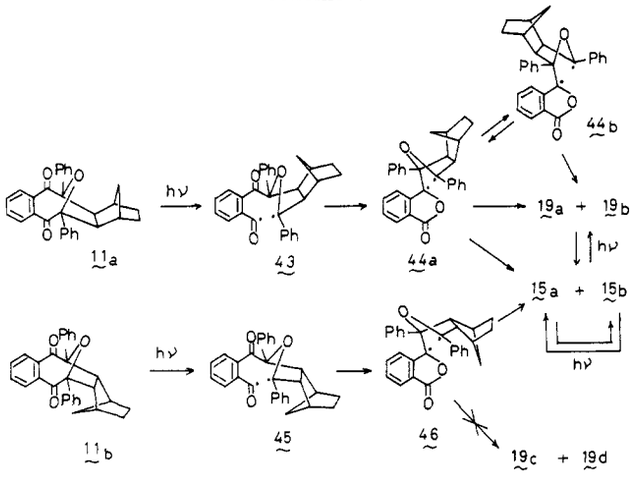


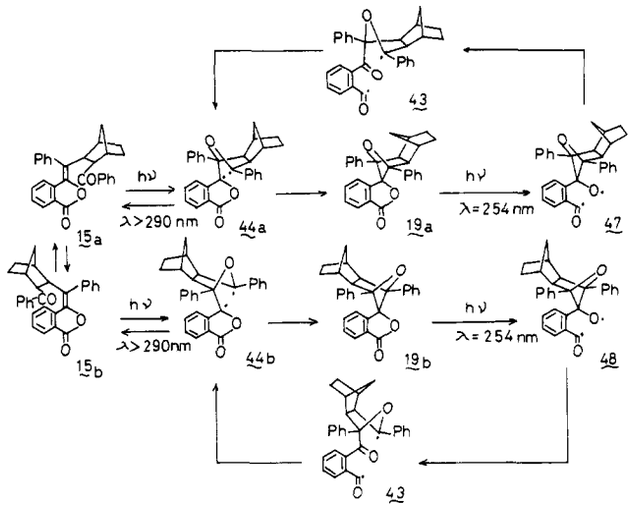
Figure 2. UV absorption spectra of **11a, 15a,** and **19a** in chloroform: **11a** (- - -), **15a** (—), and **19a** (- · - · -).

Scheme V

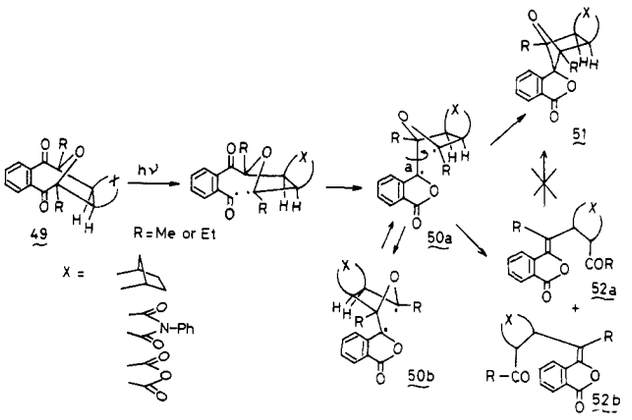


via the same intermediate **44** (or its two conformers **44a** and **44b**). On the other hand, the photoconversion of spirophthalides **19a,b** to alkylidene phthalides **15a,b** can be interpreted by the initial α cleavage of the lactone ring[13,26] to give **47** and **48.** By a subsequent β cleavage, **47** and **48** rearrange to both alkylidene phthalides **15a** and **15b** via **43** and **44.** This photointerconversion depends upon the wavelengths of the light: i.e., upon irradiation with the light of λ >290 nm, intramolecular oxetane formation **15a,b** → **19a,b** predominates, while upon irradiation with light of λ 254 nm the reverse reaction **19a,b** → **5a,b** predominates. This phenomenon could be based upon the UV light absorptivities of the relating compounds. Figure 2 shows each of the UV absorption spectra of the adduct **11a,** alkylidene phthalide **15a,** and spirophthalide **19a** observed in chloroform. The absorption spectrum of alkylidene phthalides **15a** (as well as **15b**) exhibited a strong absorption band at 323 nm (ϵ 8300), while the spectrum of **19a** (as well as **19b**) showed no absorption band above 300 nm, but characteristic absorptions at 277 and 283 nm (ϵ 3700 and 3800). Therefore, upon irradiation with the light of

Scheme VI



Scheme VII

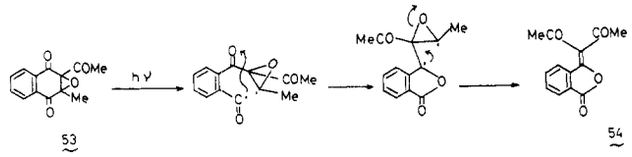


λ >300 nm, alkylidene phthalides **15a** and **15b,** with the strong absorption at >300 nm, readily rearrange to give spirophthalides **19a** and **19b,** while spirophthalides **19a** and **19b,** having no absorption at >300 nm, showed no rearrangement under the conditions, but react with light of λ >300 nm.

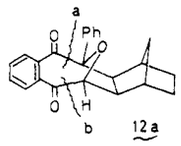
Other primary photoadducts derived from the reactions of epoxyquinones **3** and **4** with norbornene, *N*-phenylmaleimide, and maleic anhydride also undergo the photoisomerization to give spirophthalides or alkylidene phthalides (Scheme VII). However, in those cases, no intramolecular oxetane formation from alkylidene phthalides **52a** and **52b** occurred, in contrast to the case of alkylidene phthalides **15a** and **15b.** However, it is intriguing that the photoisomerization of the primary adduct **49** regardless of the substituents (R = Me and Et) gives only one of the possible isomeric spirophthalides in a good yield in every case. Probably the intermediate **50** in this photoisomerization may have the conformation as shown in **50a,** in which the norbornyl ring lies far away from the phthalide moiety, if the photoisomerization **49** → **50** would proceed according to the principle of least motion.[27] If the cyclization could occur in **50a** without rotation around the bond a, only one isomer of the possible isomeric spirophthalides would be produced (Scheme VII).

Photolysis of 2-phenyl-2,3-epoxy-2,3-dihydro-1,4-naphthoquinone (**6**) in the presence of norbornene gives no spirophthalides. Failure to isolate spirophthalides could be due to their transformation to alkylidene phthalides **16a** and **16b.** In the photoisomerization of **12a** two possible modes of bond fission (a and b) can be considered in the stage of α cleavage. Actually, only path a does occur, probably because

Scheme VIII



the resulting diradical may be more stable. Thus, α cleavage via path a and subsequent free-radical rearrangements afford the alkylidene phthalides **16a** and **16b.**



A similar photorearrangement was observed in the photolysis of 2-acetyl-3-methyl-2,3-epoxy-2,3-dihydro-1,4-naphthoquinone (**53**). Irradiation of a solution of **53** in acetonitrile gave 3-(1-acetylacetonylidene)phthalide (**54**) in 45% yield.[28] The structure of **54** was confirmed by its independent synthesis.[29] The proposed mechanism involves initial α cleavage and subsequent free-radical rearrangements (Scheme VIII).

Experimental Section

Melting points were measured with a Yanagimoto micromelting point apparatus and are uncorrected. Microanalyses were performed by the Microanalytical Laboratory of Kyoto University, Kyoto, Japan. IR spectra were recorded with a JASCO IR-G spectrophotometer, and NMR spectra were taken with a JEOL PS-100 spectrometer with tetramethylsilane as an internal standard and the chemical shifts expressed in δ values. UV spectra were recorded with a Shimadzu UV-200 spectrophotometer. Mass spectra were taken with a Hitachi M-52 mass spectrometer. Preparative TLC was carried out on Merk Kieselgel PF_{254}. UV irradiation was carried out in a Pyrex or quartz vessel at room temperature, using an Eikosha 300-W high-pressure mercury lamp or a 120-W low-pressure mercury lamp. The irradiation at >340 nm was carried out using a 300-W high-pressure mercury lamp placed in a Pyrex jacket equipped with the solution filter (aqueous solution of 2,7-dimethyl-3,6-diazacyclohepta-2,6-diene perchlorate, 0.20 g/L).

Preparation of Epoxyquinones 1–6 and 53. 2,3-Epoxy-2,3-dihydro-1,4-naphthoquinone (**1**) (mp 133–134 °C) was prepared by the method of Marmor.[30] 2-Methyl-2,3-epoxy-2,3-dihydro-1,4-naphthoquinone (**2**) (mp 96–96.5 °C) was prepared by the method of Fieser.[31] 2,3-Dimethyl-2,3-epoxy-2,3-dihydro-1,4-naphthoquinone (**3**) (mp 105–106 °C) was prepared by the epoxidation of 2,3-dimethyl-1,4-naphthoquinone with 10% aqueous sodium hypochlorite in pyridine. 2-Phenyl-2,3-epoxy-2,3-dihydro-1,4-naphthoquinone (**6**) (mp 65–66 °C) was prepared by the epoxidation of 2-phenyl-1,4-naphthoquinone[32] with 30% aqueous hydrogen peroxide in alkaline medium. 2-Acetyl-3-methyl-1,3-epoxy-2,3-dihydro-1,4-naphthoquinone (mp 94–95 °C) was prepared by the method of Read and Ruiz.[2c]

2,3-Diethyl-2,3-epoxy-2,3-dihydro-1,4-naphthoquinone (**4**) was prepared as follows. 2,3-Diethyl-1,4-naphthoquinone was prepared by the method of Jacobsen and Torsell.[33] A solution of 5 g of 1,4-naphthoquinone, 2 g of silver nitrate, and 20 g of propionic acid in 50 mL of acetonirile and 50 mL of water was heated at 70–80 °C. A solution of 14 g of ammonium peroxydisulfate in 50 mL of water was gradually added with constant stirring at 70–80 °C, over a period of 30 min. The mixture was heated at 70–80 °C with stirring for an additional 1 h and was allowed to cool. The mixture was extracted with ether, washed with 10% aqueous sodium carbonate, and dried (Na_2SO_4). After evaporation, the resulting residue was chromatographed on silica gel. Elution with petroleum ether gave 2,3-diethyl-1,4-naphthoquinone (yield 3 g, 43%), mp 68.5–69.5 °C. To the solution of 3 g of 2,3-diethyl-1,4-naphthoquinone in 30 mL of pyridine was added 10% aqueous sodium hypochloride with shaking at room temperature, until the mixture became pale yellow and the same color remained for a few minutes. The mixture was poured into 100 mL of ice water, extracted with ether, washed with dilute hydrochloric acid, and dried (Na_2SO_4). After evaporation, the resulting residue was dissolved in 20 mL of methanol and cooled at −20 °C for 1 day, giving colorless crystals of 2,3-diethyl-2,3-epoxy-2,3-dihydro-1,4-naphthoquinone (**4**) (yield 2.5 g, 80%): mp 46–46.5 °C; IR (KBr) 1685 cm^{-1} (C=O); NMR ($CDCl_3$) δ 1.12 (t, 6 H, CH_3), 2.03 (9, 4 H, CH_2), 7.5–7.9 (m, 4 H, aromatic H); UV ($CHCl_3$) λ_{max} 264, 303 nm (ϵ 6500, 2100). Anal. Calcd for $C_{14}H_{14}O_3$: C, 73.02; H, 6.13. Found: C, 72.93; H, 6.16.

2,3-Diphenyl-2,3-epoxy-2,3-dihydro-1,4-naphthoquinone (**5**) was prepared by the epoxidation of 2,3-diphenyl-1,4-naphthoquinone[34] with 10% aqueous sodium hypochloride in pyridine: mp 163.5–164 °C; IR (KBr) 1690 (C=O) cm^{-1}; NMR ($CDCl_3$) δ 7.21 (s, 10 H, phenyl ring H), 7.76–8.22 (m, 4 H, aromatic H); UV ($CHCl_3$) λ_{max} 306 (ϵ 2400). Anal. Calcd for $C_{22}H_{14}O_3$: C, 80.97; H, 4.32. Found: C, 80.71; H, 4.32.

The UV absorption spectrum of 2,3-epoxy-2,3-dihydro-1,4-naphthoquinone (**1**) in cyclohexane exhibited four absorption bands at 227 (ϵ 25 000), 263 (7500), 303 (2100), and 341 nm (230). The last weak band at 341 nm is attributed to the n → π^* transition.

Irradiation of 1 Mixed with Norbornene. A solution of 2,3-epoxy-2,3-dihydro-1,4-naphthoquinone (**1**) (300 mg) and norbornene (500 mg) in benzene (30 mL) was irradiated in a Pyrex tube for 30 h. Isolation of the products by preparative TLC gave the stereoisomeric oxetanes **7a** and **7b** (279 mg, 60%). NMR analysis indicated that the isomer ratio was **7b/7a** = 1.4:1. Two isomers were each separated by preparative TLC. The minor isomer **7a:** mp 181–182 °C (from benzene–hexane); IR (KBr) 1689 (C=O), 880, 850 cm^{-1} (oxirane ring); NMR ($CDCl_3$) δ 0.9–1.8 (m, 4 H), 1.56 (br d, 1 H, H_a-9′, J = 10 Hz), 2.37 (br s, 1 H, H-1′), 2.56 (br d, 1 H, H_s-9′, J = 10 Hz), 3.09 (d, 1 H, H-5′, J = 5 Hz), 3.12 (br s, 1 H, H-6′), 3.73 (d, 1 H, H-3, J = 4 Hz), 4.36 (d, 1 H, H-2, J = 4 Hz), 4.92 (d, 1 H, H-2′, J = 5 Hz), 7.36–8.20 (m, 4 H, aromatic H). Anal. Calcd for $C_{17}H_{16}O_3$: C, 76.10; H, 6.01. Found: C, 76.05; H, 5.92. The major isomer **7b:** mp 158 °C; IR (KBr) 1690 (C=O), 890, 860 cm^{-1} (oxirane ring); NMR ($CDCl_3$) δ 0.70–1.80 (m, 6 H), 2.47 (d, 1 H, H-5′, J = 5 Hz), 2.53 (m, 2 H, H-1′ and H-6′), 3.68 (d, 1 H, H-3, J = 4.5 Hz), 4.36 (d, 1 H, H-2, J = 4.5 Hz), 4.96 (d, 1 H, H-3′, J = 5 Hz), 7.16–7.96 (m, 4 H, aromatic H). Anal. Calcd for $C_{17}H_{16}O_3$: C, 76.10; H, 6.01. Found: C, 76.09; H, 6.04.

Irradiation of 2 Mixed with Norbornene. A solution of 2-methyl-2,3-epoxy-2,3-dihydro-1,4-naphthoquinone (**2**) (300 mg) and norbornene (500 mg) in 30 mL of benzene was irradiated for 50 h. Isolation of photoproducts by preparative TLC gave two stereoisomeric oxetanes **8a** and **8b** (381 mg, 86%). NMR analysis indicated the mixture of equal amounts of two isomers **8a** and **8b.** Only one isomer (**8b,** 116 mg, 26%) was separated and crystallized from the mixture of two isomers: mp 200–201 °C (from benzene–hexane); IR (KBr) 1690 (C=O), 873 cm^{-1} (oxirane ring); NMR ($CDCl_3$) δ 0.9–1.8 (m, 6 H), 1.66 (s, 3 H, CH_3), 2.40 (d, 1 H, H-5′, J = 5.0 Hz), 2.54 (m, 2 H, H-1′ and H-6′), 4.21 (s, 1 H, H-2), 4.92 (d, 1 H, H-3′, J = 5.0 Hz), 7.3–7.9 (m, 4 H, aromatic H); mass spectrum m/e 282 (M^+), 94, 66 (base). Anal. Calcd for $C_{18}H_{18}O_3$: C, 76.57; H, 6.43. Found: C, 76.40; H, 6.33.

Reduction of **8b** (50 mg) with sodium borohydride (20 mg) in ethanol (10 mL) at room temperature gave 2,3-epoxy-4-hydroxy-1,2,3,4-tetrahydronaphthalene-1-spiro-4′-(3′-oxatricyclo[4.2.1.-$0^{2',5'}$]nonane) (**9**) as white needles (40 mg, 80%): mp 212–218 °C dec; IR (KBr) 3400 (OH), 880 cm^{-1} (oxirane ring); NMR ($CDCl_3$) δ 0.8–1.7 (m, 6 H), 1.62 (s, 3 H, CH_3), 2.12 (br d, 1 H, OH, J = 10 Hz), 2.37 (d, 1 H, H-5′, J = 5 Hz), 2.53 (m, 2 H, H-1′ and H-6′), 3.79 (s, 1 H, H-2), 4.55 (d, 1 H, H-4, J = 10 Hz), 4.81 (d, 1 H, H-3′, J = 5.0 Hz), 7.15–7.70 (m, 4 H, aromatic H); mass spectrum m/e 284 (M^+), 94, 66 (base). Anal. Calcd for $C_{18}H_{20}O_3$: C, 76.03; H, 7.09. Found: C, 76.12; H, 7.06.

General Procedure for the Photochemical Reactions of Epoxyquinones 3–6 with Norbornene. A solution of epoxyquinones **3–6** (200–300 mg) and norbornene (200–300 mg) in benzene or acetonitrile (30 mL) was irradiated in a Pyrex or quartz tube for a suitable time, using a 300-W high-pressure or 120-W low-pressure mercury lamp. After removal of solvent the products were separated by preparative TLC, developing two or three times with 3:1 chloroform–hexane. The primary photoadducts **10–12** and spirophthalides **17–19a** developed at R_f ~0.7, alkylidene phthalides **13a–16a** or spirophthalide **19b** at R_f 0.4–0.6, and alkylidene phthalides **13b–16b** at R_f 0.2–0.3. Thus, the photoproducts were separately obtained by preparative TLC or fractional crystallizations. The results were summarized in Table I.

Physical Data of the Products Derived from the Photochemical Reactions of Epoxyquinones 3–6 with Norbornene. Perhydro-1,3-dimethyl-1,3-epoxy-4,7-methano-2*H*-indene-2-spiro-3′-phthalide (**17**): colorless crystals; mp 131.5–133 °C; IR (KBr) 1760 (C=O), 1610, 1590, 1470, 1450 cm^{-1}; UV ($CHCl_3$) λ_{max} 277, 285 nm (ϵ 2900 and 2800); mass spectrum m/e 296 (M^+), 255 (base), 149, 86. Anal. Calcd for $C_{19}H_{20}O_3$: C, 77.00; H, 6.80. Found: C, 76.79; H, 6.73.

5,12-Dimethyl-1,2,3,4,4aβ,5,12,12aβ-octahydro-5α,12α-epoxy-1α,4α-methanodibenzo[a,e]cyclooctene-6,11-dione (**10**): mp 160–161 °C; IR (KBr) 1680 (C=O), 1590, 1440 cm^{-1}; UV ($CHCl_3$) λ_{max} 253, 297, 328 nm (ε 880, 1700, 680). Anal. Calcd for $C_{19}H_{20}O_3$: C, 77.00; H, 6.80. Found: C, 77.23; H, 6.89.

(*Z*)-3-[1-(3-Acetylnorbornan-2-yl)ethylidene]phthalide (**13a**): mp 148–148.5 °C; IR (KBr) 1760, 1700 (C=O), 1650 (C=C), 1610, 1585, 1470 cm^{-1}; NMR ($CDCl_3$) δ 1.16–1.76 (m, 6 H), 1.93 (s, 3 H, CH_3), 2.10 (s, 3 H, CH_3), 2.37 (br s, 2 H, H-1 and H-4), 3.10, 3.43 (AB q, 2 H, H-2 and H-3), 7.16–7.76 (m, 4 H, aromatic H); UV ($CHCl_3$) λ_{max} 270, 322 nm (ε 17 000, 8700); mass spectrum *m/e* 296 (M^+), 255, 149 (base), 43, 41. Anal. Calcd for $C_{19}H_{20}O_3$: C, 77.00; H, 6.80. Found: C, 76.87; H, 6.81.

(*E*)-3-[1-(3-Acetylnorbornan-2-yl)ethylidene]phthalide (**13b**): mp 146–147 °C; IR (KBr) 1755, 1695 (C=O), 1601, 1580, 1468 cm^{-1}; NMR ($CHCl_3$) δ 1.23–1.90 (m, 5 H), 1.83 (s, 3 H, CH_3), 2.03 (s, 3 H, CH3), 2.16 (br d, H_s-7, *J* = 10 Hz), 1 H, 2.40 (br s, 1 H, H-4), 2.51 (br s, 1 H, H-1), 3.22, 3.49 (AB q, 2 H, H-2 and H-3, *J* = 10 Hz), 7.33–7.99 (m, 4 H, aromatic H); UV ($CHCl_3$) λ_{max} 270, 317 nm (ε 17 000, 8700). Anal. Calcd for $C_{19}H_{20}O_3$: C, 77.00; H, 6.80. Found: C, 76.91; H, 6.76.

Perhydro-1,3-diethyl-1,3-epoxy-4,7-methano-2*H*-indene-2-spiro-3′-phthalide (**18**): mp 145–146 °C (from hexane); IR (KBr) 1770 (C=O), 1605, 1590, 1465 cm^{-1}; UV ($CHCl_3$) λ_{max} 278, 286 nm (γ 2100, 2060). Anal. Calcd for $C_{21}H_{24}O_3$: C, 77.75; H, 7.46. Found: C, 77.60; H, 7.49.

(*Z*)-3-[1-(3-propionylnorbornan-2-yl)propylidene]phthalide (**14a**): mp 119–120 °C (from hexane); IR (KBr) 1756, 1705 (C=O), 1645 (C=C), 1603, 1580, 1470 cm^{-1}; NMR (CCl_4) δ 0.74 (t, 3 H, CH_3), 1.23 (t, 3 H, CH_3), 1.0–1.8 (m, 5 H), 2.09 (d, 1 H, H_s-7, *J* = 10 Hz), 2.12–2.84 (m, 6 H), 3.20, 3.37 (AB q, 2 H, H-2 and H-3, *J* = 9 Hz), 7.36–8.04 (m, 4 H, aromatic H). Anal. Calcd for $C_{21}H_{24}O_3$: C, 77.75; H, 7.46. Found: C, 77.95; H, 7.51.

(*E*)-3-[1-(3-Propionylnorbornan-2-yl)propylidene]phthalide (**14b**): mp 129–130 °C (from hexane); IR (KBr) 1768, 1700 (C=O), 1640 (C=C), 1610, 1585, 1475, 1460 cm^{-1}; NMR (CCl_4) δ 0.74 (t, 3 H, CH_3), 1.18 (t, 3 H, CH_3), 1.1–2.86 (m, 12 H), 3.12, 3.42 (AB q, 2 H, H-2 and H-3, *J* = 10 Hz), 7.4–8.1 (m, 4 H, aromatic H). Anal. Calcd for $C_{21}H_{24}O_3$: C, 77.75; H, 7.46. Found: C, 77.87; H, 7.48.

5,12-Diphenyl-1,2,3,4,4aβ,5,12,12aβ-octahydro-5α,12α-epoxy-1α,4α-methanodibenzo[a,e]cyclooctene-6,11-dione (**11a**): mp 279–280 °C (from benzene–hexane); IR (KBr) 1687 (C=O), 1590, 1493, 1449 cm^{-1}; UV ($CHCl_3$) λ_{max} 290, 332 nm (ε 1700, 2600); mass spectrum *m/e* 420 (M^+, base), 379, 353, 315, 105. Anal. Calcd for $C_{29}H_{24}O_3$: C, 82.83; H, 5.75. Found: C, 82.74; H, 5.71.

5,12-Diphenyl-1,2,3,4,4aα,5,12,12aα-octahydro-5α,12α-epoxy-1β,4β-methanodibenzo[a,e]cyclooctene-6,11-dione (**11b**): mp 226.5–227.5 °C (from benzene–hexane); IR (KBr) 1690 (C=O), 1595, 1490, 1450 cm^{-1}; UV ($CHCl_3$) λ_{max} 333 nm (ε 1800); mass spectrum *m/e* 420 (M^+, base), 379, 353, 315, 105. Anal. Calcd for $C_{29}H_{24}O_3$: C, 82.83; H, 5.75. Found: C, 82.91; H, 6.04.

(*E*)-3-[α-(3-Benzoylnorbornan-2-yl)benzylidene]phthalide (**15a**): mp 179–180 °C (from benzene–hexane); IR (KBr) 1770, 1665 (C=O), 1645 (C=C), 1605, 1593, 1590, 1475, 1448 cm^{-1}; UV($CHCl_3$) λ_{max} 272, 323 nm (ε 15 000, 9000); mass spectrum *m/e* 420 (M^+, base), 379, 353, 315, 105. Anal. Calcd for $C_{29}H_{24}O_3$: C, 82.83; H, 5.75.

(*Z*)-3-[α-(Benzoylnorbornan-2-yl)benzylidene]phthalide (**15b**): mp 227–228 °C (from benzene–hexene); IR (KBr) 1770, 1670 (C=O), 1640 (C=C), 1610, 1600, 1580, 1490, 1470, 1440 cm^{-1}; UV spectrum ($CHCl_3$) λ_{max} 273, 323 nm (ε 14 000, 8300); mass spectrum *m/e* 420 (M^+, base), 379, 353, 315, 105. Anal. Calcd for $C_{29}H_{24}O_3$: C, 82.83; H, 5.75. Found: C, 83.04; H, 5.75.

Perhydro-1,3-diphenyl-1,3-epoxy-4,7-methano-2*H*-indene-2-spiro-3′-phthalide (**19a**): mp 183–184 °C (from hexane–benzene); IR (KBr) 1767 (C=O), 1600, 1465, 1448 cm^{-1}; UV ($CHCl_3$) λ_{max} 283, 286 (ε 3300, 3400); mass spectrum *m/e* 420 (M^+, base), 379, 353, 315, 221, 105. Anal. Calcd for $C_{29}H_{24}O_3$: C, 82.83; H, 5.75. Found: C, 82.78; H, 5.54. **19b:** 223–224 °C (from benzene–hexane); IR (KBr) 1755 (C=O), 1610, 1590, 1450 cm^{-1}; UV ($CHCl_3$) λ_{max} 288 nm (ε 3800); mass *m/e* 420 (M^+, base), 379, 353, 221, 105. Anal. Calcd for $C_{29}H_{24}O_3$: C, 82.83; H, 5.75. Found: C, 82.95; H, 5.65.

5-Phenyl-1,2,3,4,4aβ,5,12,12aβ-octahydro-5α,12α-epoxy-1α,-4α-methanodibenzo[a,e]cyclooctene-6,11-dione (**12a**): mp 192–192.5 °C (from hexane–benzene); IR (KBr) 1690 (C=O), 1590, 1492, 1448 cm^{-1}. Anal. Calcd for $C_{23}H_{20}O_3$: C, 80.21; H, 5.85. Found: C, 80.20; H, 5.95. The endo,exo isomer **12b** was obtained, contaminated with **12a.** The NMR spectrum of the mixture showed the characteristic signals of **12b** at δ 5.04 (d, 1 H, H_A, *J* = 9 Hz) and 0.58 (d, 1 H, H_s-7, *J* = 10 Hz), besides the signals of **12a.**

(*Z*)-3-(3-Benzoylnorbornan-2-yl)methylidenephthalide (**16a**): mp 141–142 °C (from benzene–hexane); IR (KBr) 1775 (lactone C=O), 1672 (phenyl C=O), 1600, 1577, 1475, 1451 cm^{-1}; NMR ($CDCl_3$) δ 1.2–1.9 (m, 5 H), 2.05 (d, 1 H, H_s-7, *J* = 10 Hz), 2.21 (br s, 1 H, H-1), 2.69 (br s, 1 H, H-4), 3.60 (m, 2 H, H-2 and H-3), 5.20 (sextet, 1 H, H_A, *J* = 11, 4, and 6 Hz), 7.0–7.9 (m, 9 H, aromatic H). Anal. Calcd for $C_{23}H_{20}O_3$: C, 80.21; H, 5.85. Found: C, 80.25; H, 5.73.

(*E*)-3-(3-Benzoylnorbornan-2-yl)methylidenephthalide (**16b**): mp 110–111 °C; IR (KBr) 1775 (lactone C=O), 1670 (phenyl C=O), 1615, 1599, 1582, 1476, 1452 cm^{-1}; NMR ($CDCl_3$) δ 1.2–1.9 (m, 5 H), 2.01 (d, 1 H, H_s-7, *J* = 10 Hz), 2.22 (br s, 1 H, H-1), 2.69 (br s, 1 H, H-4), 3.41 (dd, 1 H, H-2, *J* = 9 and 11 Hz), 3.62 (d, 1 H, H-3, *J* = 9 Hz), 5.42 (d, 1 H, H_A, *J* = 11 Hz), 6.82–7.80 (m, 9 H, aromatic H).

Anal. Calcd for $C_{23}H_{20}O_3$: C, 80.21; H, 5.85. Found: C, 80.43; H, 5.83.

Reduction of 17 with Lithium Aluminum Hydride in Ether. The spirophthalide **17** (120 mg), dissolved in dry ether (20 mL), was reduced with lithium aluminum hydride (10 mg). The mixture was refluxed for 1 h with continuous stirring. After addition to ice-cold water and treatment with aqueous ammonium chloride solution, the ethereal solution was washed with water and dried (Na_2SO_4). The evaporation of the ethereal solution gave crystals (77 mg, 64%) of perhydro-1,3-dimethyl-2β-hydroxy-2α-(*o*-hydroxymethylphenyl)-1α,3α-epoxy-4α,7α-methano-2*H*-indene (mp 100–101 °C), which was acetylated with acetic anhydride in pyridine to afford perhydro-1,3-dimethyl-2β-hydroxy-2α-(*o*-acetoxymethylphenyl)-1α,3α-epoxy-4α,7α-methano-2*H*-indene (**24**) in quantitative yield: mp 105.5–106.5 °C (from hexane); IR (KBr) 3380 (s, OH), 1715 (s, $OCOCH_3$), 1606 (w), 1450 (m) cm^{-1}; NMR ($CDCl_3$) δ 0.85 (d, 1 H, H_s-7, *J* = 9 Hz), 1.0–1.7 (m, 4 H), 1.30 (s, 6 H, CH_3), 2.04 (s, 3 H, CH_3), 2.18 (s, 2 H, H-2 and H-3), 2.37 (s, 2 H, H-1 and H-4), 2.43 (d, 1 H, H_s-7), 3.42 (s, 1 H, OH), 5.14 (s, 2 H, CH_2OAc), 7.10–7.86 (m, 4 H, aromatic H). Anal. Calcd for $C_{21}H_{26}O_4$: C, 73.66; H, 7.66. Found: C, 73.48; H, 7.67.

Ozonolysis of 15a or 15b. A solution of 100 mg of **15b** in 20 mL of methylene chloride was treated with ozonized oxygen at −70 °C (dry ice–acetone). After 30 min the ozonization was discontinued and the mixture was stirred with 20 mL of water for 10 h at room temperature. The organic layer was separated and dried (Na_2SO_4). After evaporation the resulting residue was chromatographed on silica gel. The elution of petroleum ether–ether (10:1) gave the mixture of 2α,3α-dibenzoylnorbornane (**22**) and 2α-benzoyl-3α-phenoxycarbonylnorbornane (**23**), which was each separated by preparative TLC; 19 mg (25%) of **22** and 22 mg (30%) of **23** were obtained. The elution with petroleum ether–ether (1:5) gave phthalic anhydride (mp 135–136 °C) (20 mg, 57%), together with a small amount of phthalic acid (5 mg).

22: mp 144–146 °C (from hexane); IR (KBr) 2960, 2900, 2880 (alkane), 1678 (C=O), 1600, 1582, 1450 cm^{-1}; NMR ($CDCl_3$) δ 1.28 (d, 1 H, H_a-7, *J* = 10 Hz), 1.40–1.86 (m, 4 H), 1.98 (d, 1 H, H_s-7, *J* = 10 Hz), 2.73 (br s, 2 H, H-1 and H-4), 3.69 (s, 2 H, H-2 and H-3, *J* = 1.7 Hz), 7.1–7.48 (m, 6 H), 7.6–7.84 (m, 4 H); mass *m/e* 304 (M^+), 302 (base), 237, 199, 133, 105. Anal. Calcd for $C_{21}H_{20}O_2$: C, 82.86; H, 6.62. Found: C, 82.87; H, 6.59.

23: mp 134–135 °C (from benzene–hexane); IR (KBr) 2960, 2880 (alkane), 1760 (COOPh), 1672 (COPh), 1592, 1577, 1485, 1450 cm^{-1}; NMR ($CDCl_3$) δ 1.26 (d, 1 H, H_a-7, *J* = 10 Hz), 1.2–1.9 (m, 4 H), 2.16 (d, 1 H, H_s-7, *J* = 10 Hz), 2.64 (br s, 1 H, H-4), 2.82 (br s, 1 H, H-1), 3.02, 3.88 (AB q, 2 H, H-2 and H-3, *J* = 10 Hz), 6.8–8.07 (m, 10 H, aromatic H). Anal. Calcd for $C_{21}H_{20}O_3$: C, 78.72; H, 6.29. Found: C, 78.75; H, 6.10.

Ozonolysis of **15a** gave the same products as that of **15b.** However, the reaction was not so clean in the case of **15a** and a large amount of unidentified materials was formed.

Pyrolysis and Reduction of 19a and 19b. A solution of **19a** (42 mg) in xylene (10 mL) was refluxed for 1 h. Evaporation of the solvent gave crystals of (*E*)-3-[α-(3-benzoylnorbornan-2-yl)benzylidene]-phthalide (**15a**) (33 mg, 79%). Similarly a solution of **19b** (34 mg) in xylene (10 mL) was refluxed for 1 h. Evaporation of the solvent gave crystals of (*Z*)-3-[α-(3-benzoylnorbornan-2-yl)benzylidene]phthalide (**15b**) (27 mg, 79%).

The spirophthalide **19a** or **19b** (100 mg), dissolved in dry ether (10 mL), was reduced with lithium aluminum hydride (10 mg). The mixture was refluxed for 1 h with continuous stirring. Ice-cold water was added to the reaction mixture and afterwards 10% aqueous ammonium chloride was added. The mixture was extracted with water and dried (Na_2SO_4). The evaporation of ether gave crystals of perhydro-1,3-diphenyl-2β-hydroxy-2α-(*o*-hydroxymethylphenyl)-1α,3α-epoxy-4α,7α-methano-2*H*-indene (**20a**) (60 mg, 59%), or perhydro-1,3-diphenyl-2α-hydroxy-2β-(*o*-hydroxymethylphenyl)-1α,3α-epoxy-4α,7α-methano-2*H*-indene (**20b**) (54 mg, 53%), respectively.

20a: mp 145–146 °C (from benzene–hexane); IR (KBr) 2370 (OH), 2950, 2880 (alkane), 1605, 1492, 1448 cm^{-1}; NMR ($CDCl_3$) δ 0.92 (d,

1 H, H_a-7, J = 10 Hz), 1.0–1.7 (m, 4 H), 2.0 (br s, 1 H, OH), 2.47 (s, 2 H, H-1 and H-4), 2.63 (br d, 1 H, H_s-7, J = 10 Hz), 3.81 (s, 2 H, H-2 and H-3), 3.97 (s, 2 H, CH_2OH), 4.12 (br s, 1 H, OH), 7.1–7.9 (m, 14 H, aromatic H). Anal. Calcd for $C_{29}H_{28}O_3$: C, 82.05; H, 6.65. Found: C, 82.49; H, 6.45.

The compound **20b** (mp 187–188 °C) was acetylated with acetic anhydride in pyridine to afford perhydro-1,3-diphenyl-2α-hydroxy-2β-(*o*-acetoxymethylphenyl)-1α,3α-epoxy-4α,7α-methano-2*H*-indene: mp 129–139 °C (from hexane); IR (KBr) 3425 (OH), 2940, 2880 (alkane), 1727 ($OCOCH_3$), 1610, 1580, 1495, 1450 cm^{-1}; NMR ($CDCl_3$) δ 0.77 (d, 1 H, H_a-7, J = 10 Hz), 1.0–1.7 (m, 4 H), 1.88 (s, 3 H, $OCOCH_3$), 2.45 (s, 2 H, H-1 and H-4), 2.58 (br d, 1 H, H_s-7, J = 10 Hz), 2.75 (s, 2 H, H-2 and H-3), 3.80 (s, OH, 1 H), 4.43 (s, 2 H, CH_2OAc), 7.2–7.9 (m, 14 H, aromatic H). Anal. Calcd for $C_{31}H_{30}O_4$: C, 79.80; H, 6.48. Found: C, 79.83; H, 6.43.

Irradiation of 5 Mixed with Norbornadiene. (**A**) A solution of **5** (200 mg) and norbornadiene (300 mg) in benzene (30 mL) was irradiated at >340 nm for 7.5 h. The products were separated by the usual workup. 5,12-Diphenyl-4aα,5,12,12aα-tetrahydro-5α,12α-epoxy-1β,4β-methanodibenzo[*a*,*e*]cyclooctene-6,11(*1H*,*4H*)-dione (**25**) (177 mg, 69%): mp 184–184.5 °C; IR (KBr) 1690 (C=O), 1590, 1490, 1449 cm^{-1}; NMR ($CDCl_3$) δ 0.73 (d, 1 H, H_s-7, J = 8 Hz), 1.33 (d, 1 H, H_a-7, J = 8 Hz), 2.63 (br s, 2 H, H-1 and H-4), 3.12 (s, 2 H, H-2 and H-3), 6.16 (br s, 2 H, olefinic H), 7.08–7.58 (m, 10 H, aromatic H), 7.80 (m, 4 H, aromatic H). Anal. Calcd for $C_{29}H_{22}O_3$: C, 83.23; H, 5.30. Found: C, 83.20; H, 5.26.

(*E*)-3-[α-(3-Benzoyl-5-norbornen-2-yl)benzylidene]phthalide (26a) (52 mg, 20%) and (*Z*)-3-[α-(3-Benzoyl-5-norbornen-2-yl)benzylidene]phthalide (26b) (17 mg, 6%). (**B**) Irradiation of a solution of **5** (400 mg) and norbornadiene (500 mg) in benzene (60 mL) in a quartz tube for 40 h using a low-pressure mercury lamp gave **26a** and **26b** as the main products. After evaporation of benzene the resulting residue was chromatographed on silica gel using petroleum ether–ether as the developing solution. The first fractions gave **26a** (180 mg, 35%) as colorless crystals. The second fractions gave the spirophthalide **27b** (30 mg, 6%). The third fractions gave **26b** (220 mg, 43%) as colorless plates. **26a:** mp 163–164 °C; IR (KBr) 1765, 1668 (C=O), 1600, 1470, 1445 cm^{-1}; NMR ($CDCl_3$) δ 1.24 (cd, 1 H, H_a-7, J = 9 Hz), 1.80 (d, 1 H, H_s-7, J = 0 Hz), 2.88 (br s, 1 H, H-4), 3.02 (br s, 1 H, H-2), 3.75, 4.05 (AB q, 2 H, H-2 and H-3, J = 9 Hz), 5.76 (dd, 1 H, H_A, J = 7 and 2 Hz), 6.37 (br s, 2 H, olefinic H), 7.0–7.7 (m, 16 H, aromatic H), 8.02 (m, 2 H, aromatic H). Anal. Calcd for $C_{29}H_{22}O_3$: C, 83.23; H, 5.30. Found: C, 83.49; H, 5.41. **26b:** mp 195–196 °C; IR (KBr) 1763, 1668 (C=O), 1598, 1450 cm^{-1}; NMR ($CDCl_3$) δ 1.26 (d, 1 H, H_a-7, J = 8 Hz), 1.73 (d, 1 H, H_s-7, J = 8 Hz), 3.06 (br s, 2 H, H-1 and H-4), 3.76, 4.00 (AB q, 2 H, H-2 and H-3, J = 9 Hz), 6.43 (br s, 2 H, olefinic H), 6.9–7.1 (m, 14 H, aromatic H). Anal. Calcd for $C_{29}H_{22}O_3$: C, 83.23; H, 5.30. Found: C, 83.16; H, 5.25.

(**C**) A solution of **5** (500 mg) and norbornadiene (1 g) in benzene (400 mL) was irradiated at >340 nm for 15 h. After evaporation of the solvent, the residue was chromatographed on silica gel using petroleum ether–ether as the eluent. The fractions gave 1,3-diphenyl-1,3,4,4aβ,7,7aβ-hexahydro-1α,3α-epoxy-4α,7α-methano-2*H*-indene-2-spiro-3′-phthalide (**27a**) (292 mg, 46%) as colorless crystals: mp 164.5–165.5 °C (from benzene–hexane); IR (KBr) 1779 (lactone C=O), 1610, 1495, 1468, 1450 cm^{-1}; NMR ($CDCl_3$) δ 1.18 (d, 1 H, H_a-7, J = 9 Hz), 2.73 (br s, 2 H, H-1 and H-4), 3.08 (d, 1 H, H_s-7), 3.12 (s, 2 H, H-2 and H-3), 6.32 (br s, 2 H, olefinic H), 7.1–7.8 (m, aromatic H). Anal. Calcd for $C_{29}H_{22}O_3$: C, 83.23; H, 5.30. Found: C, 82.72; H, 5.28.

The second fractions gave **26a** (50 mg, 8%). The third fractions gave another isomer of **27a**, i.e., **27b** (211 mg, 33%) as colorless plates: mp 195–196 °C; IR (KBr) 1760 (lactone C=O), 1610, 1590, 1495, 1465, 1450 cm^{-1}; NMR ($CDCl_3$) δ 1.16 (d, 1 H, H_a-7, J = 9 Hz), 2.97 (br s, 1 H, H-1 and H-4), 3.12 (br d, 1 H, H_s-7, J = 9 Hz), 3.20 (s, 2 H, H-2 and H-3), 6.50 (s, 2 H, olefinic H), 7.2–8.03 (m, 4 H, aromatic H). Anal. Calcd for $C_{29}H_{22}O_3$: C, 83.23; H, 5.30. Found: C, 83.47; H, 5.29.

Irradiation of 6 Mixed with Norbornadiene. A solution of **5** (200 mg) and norbornadiene (200 mg) in benzene (30 mL) was irradiated in a Pyrex tube for 6 h. The products were separated by preparative TLC, developing with 3:1 chloroform–hexane. The R_f ~0.7 band gave 5-phenyl-4aβ,5,12,12aβ-tetrahydro-5α,12α-epoxy-1α,4α-methanodibenzo[*a*,*e*]cyclooctene-6,11(1*H*,4*H*)-dione **28a** (135 mg, 49%). Crystallization from methanol gave pure crystals of **28:** mp 215–216 °C; IR (KBr) 1680 (C=O), 1590, 1485, 1445 cm^{-1}; NMR ($CDCl_3$) δ 1.17 (d, 1 H, H_a-7, J = 10 Hz), 1.74 (d, 1 H, H_s-7, J = 10 Hz), 2.57 (s, 1 H, H-4), 2.62 (dd, 1 H, H-3), 3.01 (d, 1 H, J = 7 Hz), 3.10 (s, 1 H, H-1), 4.65 (d, 1 H, H_A, J = 2 Hz), 6.20 (br s, 2 H, olefinic H), 7.1–7.9 (m, 9 H, aromatic H). Anal. Calcd for $C_{23}H_{18}O_3$: C, 80.68; H, 5.30. Found: C, 80.62; H, 5.15.

Irradiation of 5 Mixed with *N*-Phenylmaleimide. (**A**) A solution of **5** (200 mg) and *N*-phenylmaleimide (200 mg) in benzene (30 mL) was irradiated at >340 nm for 12 h. The separation of products by preparative TLC gave 128 mg (64%) of recovered **5** and 71 mg (24%) of the 1:1 adduct **29**, together with a small amount of the alkylidene phthalide **30**. 6,9-Diphenyl-5,10-dioxo-5,6,7,8,9,10-hexahydro-6α,9α-epoxybenzocyclooctene-7β,8β-*N*-phenyldicarboximide (**29**): mp 259.5–260.5 °C (fom methanol); IR (KBr) 1777 (w), 1716 (vs) (imide C=O), 1685 (s) (phenyl C=O), 1593, 1495, 1450 cm^{-1}; UV ($CHCl_3$) λ_{max} 327 nm (ϵ 2800). Anal. Calcd for $C_{32}H_{21}NO_5$: C, 76.94; H, 4.24; N, 2.80. Found. C, 76.95; H, 4.13; N, 2.57.

(**B**) A solution of **5** (200 mg) and *N*-phenylmaleimide (200 mg) in benzene (30 mL) was irradiated at >340 nm for 20 h. The separation of the products by preparative TLC gave a mixture of **29** and **30** (150 mg, 58%) whose isomer ratio was 2:1 estimated by NMR. These products were each separated by column chromatography on silica gel using petroleum ether–ether. (*E*)-3-(α-phthalylidenebenzyl)-4-benzoyl-*N*-phenylsuccimide (**30**): mp 236–237 °C (from ethanol); IR (KBr) 1770 (s), 1710 (s), 1682 (s), 1595 (m), 1492 (m), 1472 (w), 1453 (w), 1445 (w) cm^{-1}; UV ($CHCl_3$) λ_{max} 277, 315 nm (ϵ 11 000, 18 000). Anal. Calcd for $C_{32}H_{21}NO_5$: C, 76.94; H, 4.24; N, 2.80. Found: C, 77.14; H, 4.10; N, 2.80.

(**C**) A solution of **5** (300 mg) and *N*-phenylmaleimide (1 g) in benzene (400 mL) was irradiated at >340 nm for 50 h. The separation of the products by the column chromatography of silica gel gave 197 mg (43%) of phthalide-3-spiro-6′-(1′,4′-diphenyl-5′-oxabicyclo[2.1.1]-hexane)-2′,3′-*N*-phenyldicarboximide (**31**) as colorless crystals: mp 244–245 °C; IR (KBr) 1784 (s), 1713 (s), 1600 (w), 1494 (m), 1466, 1451 (w) cm^{-1}; UV ($CHCl_3$) λ_{max} 280, 287 nm (ϵ 3600 and 3600). Anal. Calcd for $C_{32}H_{21}NO_5$: C, 76.94; H, 4.24; N, 2.80. Found: C, 77.14; H, 4.10; N, 2.90.

Irradiation of 5 Mixed with *N*-Phenylmaleimide. A solution of **5** (100 mg) and *N*-phenylmaleimide (200 mg) in benzene (30 mL) was irradiated at >340 nm for 3 h. Evaporation of the solvent gave a residue which crystallized on the addition of methanol. The crude crystals (202 mg, 60%) were collected and recrystallized from 3:1 ethanol–benzene (70 mL) to give pure crystals of 6-phenyl-5,10-dioxo-5,6,7,8,9,10-hexahydro-6α,9α-epoxybenzocyclooctene-7α,8α-*N*-phenyldicarboximide (**32**) as white needles: mp 270–271 °C; IR (KBr) 1780 (w), 1705 (s), 1590 (w), 1495 (m), 1450 (w) cm^{-1}. Anal. Calcd for $C_{26}H_{17}NO_5$: C, 73.75; H, 4.05; N, 3.31. Found: C, 73.99; H, 4.25; N, 3.48.

Irradiation of 3 Mixed with *N*-Phenylmaleimide. (**A**) A solution of **3** (100 mg) and *N*-phenylmaleimide (160 mg) in benzene (60 mL) was irradiated in a Pyrex tube for 15 h. Evaporation of the solvent and addition of methanol gave crude crystals of phthalide-3-spiro-6′-(1′,4′-dimethyl-5′-oxabicyclo[2.1.1]hexane)-2′α,3′α-*N*-phenyldicarboximide (**34**) (140 mg, 76%): mp >300 °C (from benzene); IR (KBr) 1765 (s), 1705 (s), 1595 (w), 1497 (m), 1465 (m); mass spectrum *m/e* 375 (M^+, base), 239, 228, 213, 183, 149, 45, 43. Anal. Calcd for $C_{22}H_{17}O_5N$: C, 70.39; H, 4.57; N, 3.73. Found: C, 70.48; H, 4.35; N, 3.53.

(**B**) A solution of **3** (300 mg) and *N*-phenylmaleimide (300 mg) in benzene (30 mL) was irradiated in a Pyrex tube for 15 h. White crystals precipitated on the wall of the reaction tube and were separated by filtration. Recrystallization of the crystals from benzene gave 6,9-dimethyl-5,10-dioxo-5,6,7,8,9,10-hexahydro-6α,9α-epoxybenzocyclooctene-7α,8α-*N*-phenyldicarboxide (**33**) (35 mg, 10%). The filtrate was evaporated and the residue was crystalized from ethanol to give **32** (120 mg, 22%). **33:** mp 292–293 °C; IR (KBr) 1785 (w), 1707 (s), 1690 (s), 1590 (m), 1501 (w), 1440 (w) cm^{-1}. Anal. Calcd for $C_{22}H_{17}O_5N$: C, 70.39; H, 4.57; N, 3.73. Found: C, 70.48; H, 4.35; N, 3.3.

Irradiation of 4 Mixed with *N*-Phenylmaleimide. A solution of **4** (100 mg) and *N*-phenylmaleimide (150 mg) in benzene (30 mL) was irradiated in a Pyrex tube for 15 h. Evaporation of the solvent gave a solid residue. Recrystallization of the crude products from methanol gave phthalide-3-spiro-6′-(1′,4′-diethyl-5′-oxabicyclo[2.1.1]-hexane)-2′α,3′α-*N*-phenyldicarboximide (**35**) (204 mg, 58%) as white needles: mp 224–225 °C; IR (KBr) 1778 (s), 1703 (s), 1610 (w), 1598 (w), 1498 (m), 1469 (m) cm^{-1}. Anal. Calcd for $C_{24}H_{21}O_4N$: C, 71.45, H, 5.25; N, 3.47. Found: C, 71.70; H, 5.39; N, 3.43.

Irradiation of 3 Mixed with Maleic Anhydride. A solution of **3** (400 mg) and maleic anhydride (300 mg) in benzene (60 mL) was irradiated at >340 nm for 20 h. Colorless crystals (355 mg, 60%) of phthalide-3-spiro-6′-(1′,4′-dimethyl-5′-oxabicyclo[2.1.1]hexane)-2′α,3′α-dicarboxylic anhydride (**37**) precipitated. Evaporation of the filtrate and crystallization of the resulting residue from benzene gave additional crystals of **37** (101 mg, 17%): mp >300 °C (from benzene); IR (KBr) 1850 (s), 1780 (vs), 1608 (w), 1600 (m), 1470 (m), 1447 (m) cm^{-1}; NMR ($CDCl_3$) δ 1.45 (s, 6 H, Me), 3.88 (s, 2 H, H-2′ and H-3′), 7.66–8.07 (m, 4 H, aromatic H). Anal. Calcd for $C_{16}H_{12}O_6$: C, 64.00;

H, 4.03. Found: C, 63.92; H, 3.99.

The primary photoadduct **36** was isolated in the following way. A solution of **3** (400 mg) and maleic anhydride (200 mg) in benzene (30 mL) was irradiated in a Pyrex tube for 15 h. The crystals which precipitated were filtered off and recrystallized from benzene to give **37**. The filtrate obtained by the removal of **37** was evaporated, and the residue was crystallized from benzene–hexane. The crystals obtained were, however, a mixture of **36** and **37**. The primary photoadduct **36** was obtained in the pure state by several fractional recrystallizations. 6,9-Dimethyl-5,10-dioxo-5,6,7,8,9,10-hexahydro-6α,9α-epoxybenzocyclooctene-7α,8α-dicarboxylic anhydride (**36**): mp 227–228 °C (from benzene–hexane); IR (KBr) 1860 (s), 1775 (vs), 1690 (s), 1590 (m), 1445 (m) cm^{-1}; NMR ($CDCl_3$) δ 1.72 (s, 6 H, CH_3), 3.95 (s, 2 H, H-7 and H-8), 7.7–7.9 (m, 4 H, aromatic H). Anal. Calcd for $C_{16}H_{12}O_6$: C, 64.00; H, 4.03. Found: C, 64.01; H, 3.95.

Irradiation of 4 Mixed with Maleic Anhydride. A solution of 4 (300 mg) and maleic anhydride (210 mg) in benzene (60 mL) was irradiated at >340 nm for 20 h. After evaporation of the solvent the oily residue was crystallized upon addition of methanol. Recrystallization of crude crystals (265 mg, 63%) from benzene gave phthalide-3-spiro-6′-(1′,4′-diethyl-5′-oxabicyclo[2.1.1]hexane)-2′α,3′α-dicarboxylic anhydride (**38**): mp 285–286 °C; IR (KBr) 1860 (m), 1775 (vs), 1613 (w), 160 (w), 1467 (m), 1450 (w) cm^{-1}; NMR ($CDCl_3$) δ 0.72 (t, 6 H, CH_2CH_3), 1.97 (m, 4 H, CH_2CH_3), 4.09 (s, 2 H, H-2′ and H-3′), 7.6–8.05 (m, 4 H, aromatic H). Anal. Calcd for $C_{18}H_{16}O_6$: C, 65.85; H, 4.91. Found: C, 66.07; H, 4.86.

Esterification of 37 with Diazomethane. To a suspension of the anhydride adduct (**37**) (100 mg) in dry methanol (20 mL) was added at room temperature an excess of an ethereal solution of diazomethane. After stirring overnight, evaporation of the solvent gave crystals of phthalide-3-spiro-6′-(1′,4′-dimethyl-2′α,3′α-dimethoxycarbonyl-5′-oxabicyclo[2.1.1]hexane) (**39**) as colorless needles in quantitative yield: mp 235–236 °C; IR (KBr) 1775 (s) 1750 (s), 1742 (s), 1615 (w), 1600 (w), 1470 (w), 1440 (m) cm^{-1}; NMR ($CDCl_3$) δ 1.38 (s, 6 H, CH_3), 3.75 (s, 6 H, $COOCH_3$), 3.82 (s, 2 H, H-2′ and H-3′), 7.5–8.1 (m, 4 H); UV ($CHCl_3$) λ_{max} 278, 286 nm (ϵ 2400 and 2500). Anal. Calcd for $C_{18}H_{18}O_7$: C, 62.42; H, 5.24. Found: C, 62.32; H, 5.18.

Irradiation of 3 Mixed with Dimethyl Maleate or with Dimethyl Fumarate. A solution of **3** (200 mg) and dimethyl maleate (500 mg) in benzene (30 mL) was irradiated in a Pyrex tube for 10 h. After removal of the solvent and excess dimethyl maleate, the resulting residue was separated by preparative TLC, developing with 3:1 chloroform–hexane. The R_f ~0.5 band contained 6,9-dimethyl-7α,8β-dimethoxycarboxyl-6,7,8,9-tetrahydro-6α,9α-epoxybenzocyclooctene-5,10-dione **40** (137 mg, 40%); mp 104–104.5 °C (from hexane); IR (KBr) 1735 (s), 1695 (s), 1685 (s), 1590 (m), 1440 (s) cm^{-1}; NMR (CCl_4) δ 1.41 (s, 3 H, CH_3), 1.70 (s, 3 H, CH_3), 3.47, 3.58 (AB q, 2 H, H-7 and H-8), 3.65 (s, 3 H, $COOCH_3$), 3.73 (s, 3 H, $COOCH_3$), 7.50–7.98 (m, 4 H, aromatic H); UV ($CHCl_3$) λ_{max} 254, 300 nm (ϵ 11 000, 5700). Anal. Calcd for $C_{18}H_{18}O_7$: C, 62.42; H, 5.24. Found: C, 62.32; H, 5.18.

Irradiation of a solution of **3** (300 mg) and dimethyl fumarate (300 mg) in benzene (30 mL) for 15 h also gave the 1:1 adduct **40** (277 mg, 52%). The adduct **40** was also obtained by treatment of the maleic anhydride adduct **36** with diazomethane.

Irradiation of 53. A solution of 2-acetyl-3-methyl-2,3-epoxy-2,3-dihydro-1,4-naphthoquinone (200 mg) in acetonitrile (30 mL) was irradiated in a Pyrex tube for 10 h using a high-pressure mercury lamp (300 W). Evaporation of the solvent gave an oily residue which crystallized on the addition of methanol. Recrystallization of the crude crystals from hexane–benzene gave 3-(1-acetylacetonilidene)-phthalide (**54**) (90 mg, 45%) as colorless needles: mp 133–134 °C; IR (KBr) 1795 (vs), 1710 (s), 1650 (s), 1620 (vs), 1590 (m), 1470 (w), 1415 (m) cm^{-1}; NMR ($CDCl_3$) δ 2.49 (s, 3 H, CH_3), 2.70 (s, 3 H, CH_3), 7.5–8.0 (m, 4 H, aromatic H); UV ($CHCl_3$) λ_{max} 283, 314 nm (ϵ 16 000, 13 000); mass spectrum m/e 230 (M^+), 188, 173. Anal. Calcd for $C_{13}H_{10}O_4$: C, 67.82; H, 4.38.

The phthalide **54** was also synthesized by another route. Condensation of phthaloyl dichloride and acetylacetone in ether with sodium gave the phthalide **54**.[29]

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Registry No.—**1**, 15448-58-5; **2**, 15448-59-6; **7a**, 57237-29-3; **7b**, 57187-98-1; **8a**, 57188-26-8; **8b**, 57237-28-2; **9**, 63688-92-6; **12b**, 63729-76-0; **13**, 63688-93-7; **14**, 63688-94-8; **16**, 63688-95-9; **20a**, 63688-96-0; **20b**, 63729-77-1; **22**, 63688-97-1; **23**, 63713-96-2; **24**, 63688-98-2; **25**, 63729-78-2; **26**, 63688-99-3; **27a**, 63713-97-3; **27b**, 63782-92-3; **28**, 63689-00-9; **36**, 63689-01-0; **37**, 63689-02-1; **38**, 63689-03-2; **39**, 63689-05-4; **53**, 40420-52-8; **54**, 7706-74-3; 2,3-dimethyl-1,4-naphthoquinone, 2197-57-1; 2-phenyl-1,4-naphthoquinone, 2348-77-8; 2,3-diethyl-1,4-naphthoquinone, 2397-59-3; 2,3-diphenyl-1,4-naphthoquinone, 33753-12-7; norbornene, 498-66-8; perhydro-1,3-dimethyl-2β-hydroxy-2α-(*o*-hydroxymethylphenyl)-1α,3α-epoxy-4α,7α-methano-2*H*-indene, 63689-06-5; perhydro-1,3-diphenyl-2α-hydroxy-2β-(*o*-acetoxymethylphenyl)-α,3α-epoxy-4α,7α,methano-2*H*-indene, 63689-07-6; norbornadiene, 121-46-0; *N*-phenylmaleimide, 941-69-5; maleic anhydride, 108-31-6; dimethyl maleate, 624-48-6.

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Reduction of 12-Keto Steroids. 2[1]

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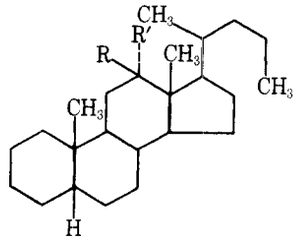
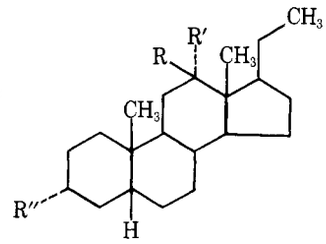
In an effort to explore the steric factors responsible for the course of the lithium–ammonia and sodium borohydride reductions of 12-keto steroids, the reductions of 24-nor-5β-cholan-12-one (**5**), 23,24-dinor-5β-cholan-12-one (**6**), and 5β-pregnan-12-one (**7**) have been studied. Under the conditions used, ketones **5** and **6** give mixtures of 12α- and 12β-ols very similar to those observed previously in the reduction of 5β-cholan-12-one (**1**). Ketone **7** and 3α-hydroxy-5β-pregnan-12-one (**3**) behave markedly differently, giving almost exclusively the 12β-ol on reduction with lithium–ammonia. The synthesis of ketones **5** and **6** is described.

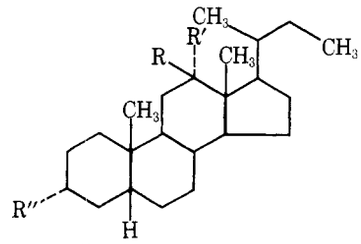
A number of years ago, we observed that dissolving metal (lithium–ammonia or sodium–alcohol) reduction of certain 12-keto steroids proceeded in what at that time was considered to be an anomalous manner.[1a] That is, reduction of compounds related to 5β-cholan-12-one (**1**) gave as the major product the thermodynamically unstable, axial 12α-ol (**2**), while reduction of 3α-hydroxy-5β-pregnan-12-one (**3**) gave the "normal" thermodynamically stable product (**4**). A mechanistic and steric explanation for these data was presented in this earlier paper.[1a] In the years following our original report, revised mechanisms for the dissolving metal reductions of ketones were suggested, some of which do not appear to permit a rationalization of the data reported in our 1964 publication.[2]



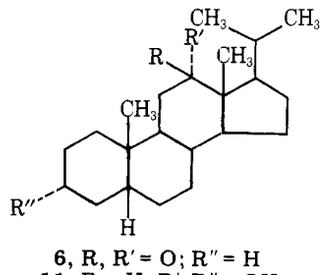
1, R, R′ = O
2, R = H; R′ = OH



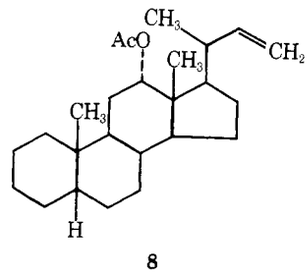
3, R, R′ = O; R″ = OH
4, R, R″ = OH; R′ = H
7, R, R′ = O; R″ = H



5, R, R′ = O; R″ = H
9, R, R″ = H; R′ = OH
10, R = H; R, R″ = OH



6, R, R′ = O; R″ = H
11, R = H; R′, R″ = OH
12, R, R″ = H; R′ = OH



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Also, the detailed nature of the steric parameters in the steroid molecule responsible for the drastically different course of reduction of ketones **1** and **3** was not known with certainty. It appeared probable that the steric effect responsible for the behavior of 12-keto steroids on reduction was shielding of the β face of the steroid molecule by the C-21 methyl group in ketone **1**, while ketone **3** is unshielded and behaves as a normal unhindered cyclohexanone. This is the explanation offered originally for the steric course of these reductions[1a] and seemed to be reinforced by the results obtained by Blickenstaff's group in studies of the rates of acetylation of a series of 12-hydroxy steroids.[3] However, an alternative explanation which seemed to be in somewhat better agreement with the recent mechanistic proposals for dissolving metal reductions[2] involved the shielding of the α face of the steroid molecule by C-24 of ketone **1**. In the case of ketone **3**, the two-carbon chain would be unable to shield the 12-carbonyl and reduction would proceed normally.

In order to ascertain which, if either, of these explanations was correct we sought to prepare 24-nor-5β-cholan-12-one (**5**) and 23,24-dinor-5β-cholan-12-one (**6**) in order to study their behavior on reduction. Also, to exclude the possibility that the 3-hydroxyl group in ketone **3** was affecting the course of the reduction of this compound, the reduction of 5β-pregnan-12-one (**7**) was to be studied.

The synthesis of ketones **5** and **6** was relatively straightforward. Ketone **5** was prepared initially from deoxycholic acid (3α,12α-dihydroxy-5β-cholan-24-oic acid) by following the known route to 12α-acetoxy-5β-cholan-24-oic acid,[4] which on decarboxylation with lead tetraacetate[5] afforded 12α-acetoxy-24-nor-5β-chol-22-ene (**8**).[6] Catalytic reduction of **8** followed by reductive cleavage of the ester gave 24-nor-5β-cholan-12α-ol (**9**). Although this synthesis afforded the precursor to ketone **5**, the overall yield was mediocre and an alternative synthesis from 24-nor-5β-cholane-3α,12α-diol (**10**)[7]