Oxidative Conversions of 2,2′-Diphenoquinone Valence Isomers with 2,3-Dichloro-5,6-dicyanobenzoquinone. Synthesis and Spectroscopic Properties of (*E*)-[3,3′]Bibenzofuranylidene-2,2′-diones (Isoxindigos)

Hans-Dieter Becker* and Hans Lingnert

Department of Organic Chemistry, Chalmers University of Technology and University of Gothenburg, S-412 96 Gothenburg, Sweden

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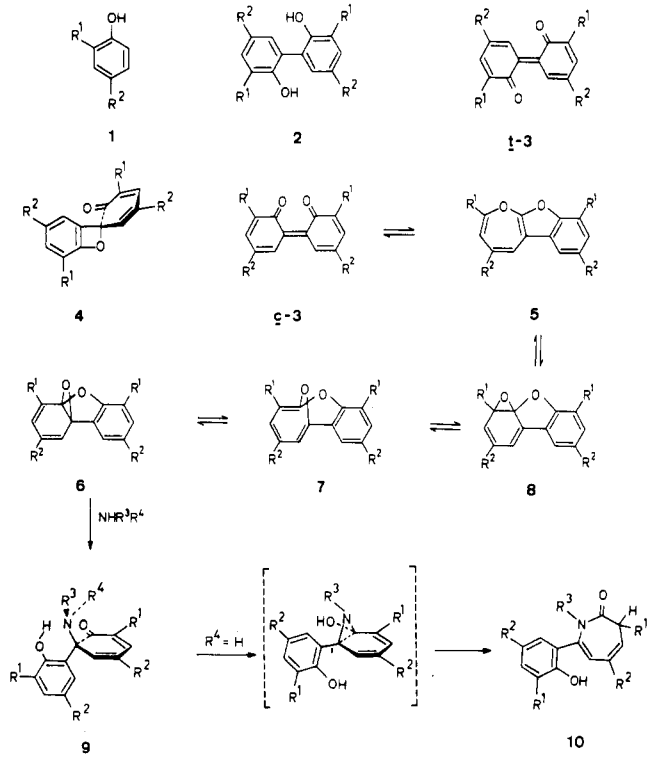
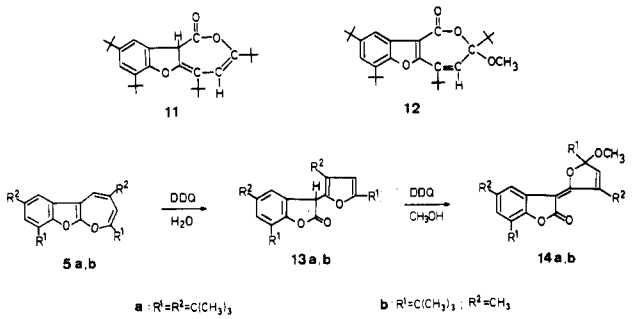
Oxepinobenzofurans derived from tetraalkyl-substituted and dialkyldimethoxy-substituted 2,2′-diphenoquinones by spontaneous valence isomerization react with 2,3-dichloro-5,6-dicyanobenzoquinone (DDQ) in the presence of water to give benzofuranyliden-2-ones whose formation is suggested to involve hydrolysis of the substrate ketal moiety. The course of the reaction and, consequently, the structure of the oxidation products were found to depend on the nature of the substrate substituents. Upon exhaustive oxidation by DDQ, benzofuranylidenones are smoothly converted into isoxindigos. A mechanism for their formation involving hydration of the exocyclic double bond, oxidative coupling, and loss of the side chain by a retro-aldol reaction is proposed. The electron spectral properties of isoxindigos and those of their isomeric dibenzonaphthyrones are compared and discussed.

The oxidation of 4-substituted 2-*tert*-butylphenols **1** or biphenols **2** with a variety of oxidants gives rise to blue or



purple 2,2′-diphenoquinones **3** which, in general, spontaneously change into colorless or pale yellow isomers.[1,2] In 1961, these isomers were suggested to be benzoxetes **4**, but a recent X-ray structure analysis has revealed that the compounds believed to be benzoxetes actually are oxepino[2,3-*b*]benzofurans **5**.[3,4] Their formation has been explained by valence isomerization of *cis*-2,2′-diphenoquinones **3**, and an equilibrium between **5** and the other conceivable valence isomers **6–8** was excluded on the basis of NMR experiments.[4] We have recently pointed out, however, that the reaction of 2,2′-diphenoquinone isomers with secondary and primary amines gives 2,4-cyclohexadienones **9** and azepinones **10**, respectively, whose formation appears more reasonably rationalized by invoking an equilibrium and by assuming that benzene oxides **6** or **8**, if not 2,2′-diphenoquinones **3**, undergo nucleophilic attack.[5]

The nucleophilic attack of a 2,2′-diphenoquinone isomer by water was reported in 1969 when the reaction of oxepinobenzofuran **5a**, then believed to be a benzoxete, with 2,3-dichloro-5,6-dicyano-1,4-benzoquinone (DDQ) in aqueous methanol was described to give a colorless lactone ($C_{28}H_{40}O_3$) which underwent further oxidation by DDQ to yield a yellow lactone ($C_{29}H_{42}O_4$).[6] These lactones were proposed to be benzofurooxepinones **11** and **12**, but their



structures were subsequently revised in favor of the furanyl-substituted 3*H*-benzofuran-2-one **13a** and the benzofuranyliden-2-one **14a**, respectively.[7] Analogous lactones **13b** and **14b** were obtained in the DDQ oxidation of 2-*tert*-butyl-4-methylphenol,[8] and the structures of **13b** and **14a** also have been confirmed by X-ray diffraction analysis.[9,10]

The present paper deals with the DDQ oxidation of the oxepinobenzofuran **5c** derived from 2-*tert*-butyl-4-methoxyphenol, and with the heretofore unknown oxidative conversion of benzofuranyliden-2-ones into isoxindigos.

Results and Discussion

Addition of DDQ (1 molar equiv) to a suspension of oxepinobenzofuran **5c** in aqueous methanol gives rise to

(1) Musso, H. In "Oxidative Coupling of Phenols"; Taylor, W. I., Battersby, A. R., Eds.; Marcel Dekker: New York, 1967; p 1.
(2) Becker, H.-D.; Gustafsson, K. *Tetrahedron Lett.* **1976**, 4883 and references therein.
(3) Müller, E.; Mayer, R.; Narr, B.; Rieker, A.; Scheffler, K. *Justus Liebigs Ann. Chem.* **1961**, *645*, 25.
(4) Meier, H.; Schneider, H. P.; Rieker, A.; Hitchcock, P. B. *Angew. Chem.* **1978**, *90*, 128.
(5) Becker, H.-D.; Gustafsson, K.; Raston, C. L.; White, A. H. *Aust. J. Chem.* **1979**, *32*, 1931.
(6) Becker, H.-D. *J. Org. Chem.* **1969**, *34*, 1198.
(7) Becker, H.-D. In "The Chemistry of the Quinonoid Compounds"; Patai, S., Ed.; Wiley-Interscience: New York, 1974; pp 335, 389.
(8) Hewgill, F. R.; Howie, G. B. *Aust. J. Chem.* **1978**, *31*, 907.
(9) Hall, S. R.; Raston, C. L.; Skelton, B. W.; White, A. H. *Aust. J. Chem.* **1978**, *31*, 923.
(10) Becker, H.-D.; Hall, S. R.; Raston, C. L.; White, A. H. *Aust. J. Chem.* **1978**, *31*, 927.

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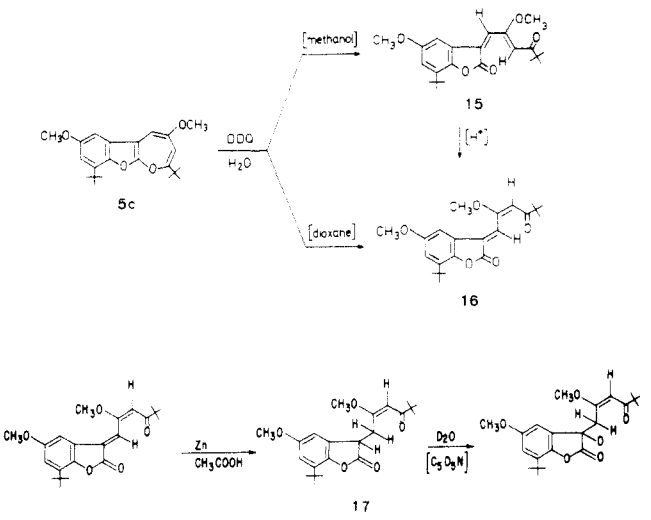
Scheme I



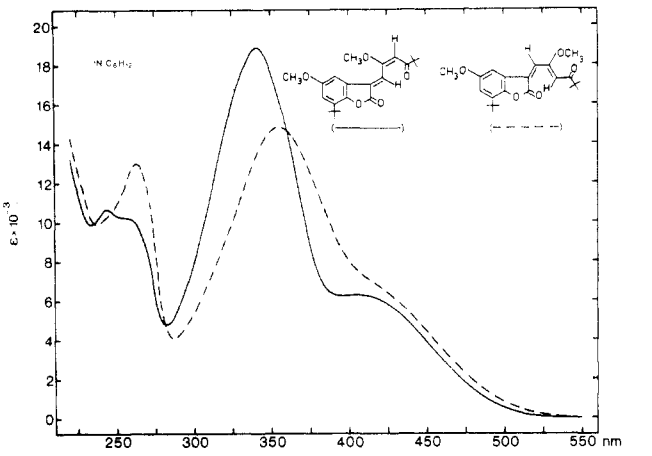
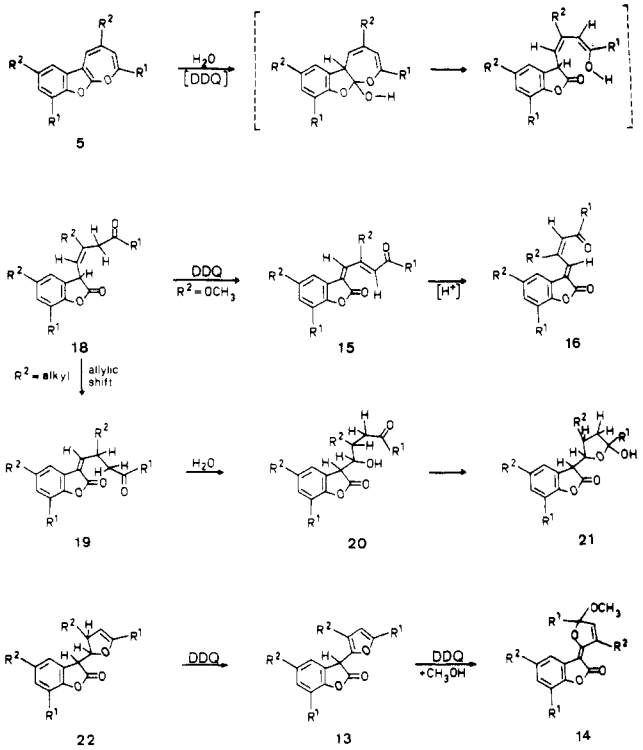


Figure 1. Electronic absorption spectra of *Z,Z* and *E,E* isomeric benzofuranylidenones **15** and **16**.

a deep brown solution from which bright orange crystals of benzofuranyliden-2-one **15** precipitate within a few minutes (Scheme I). When the oxidation of **5c** with 1 molar equiv of DDQ is carried out in aqueous dioxane, the major product (77% yield) is the geometrically isomeric benzofuranyliden-2-one **16**. Both **15** and **16** are formed as minor products in the lead tetraacetate oxidation of biphenol **2** (R^1 = *tert*-butyl, R^2 = methoxy).[11,12] They are distinguishable by their ^1H NMR spectra (see Experimental Section; cf. also ref 11), they differ in their electronic absorption spectra (see Figure 1), and their structures have been ascertained by X-ray analysis.[13,14] Upon treatment with hydrogen chloride, the *Z,Z* isomer **15** is quantitatively converted into the *E,E* isomer **16**, and both isomers are moothly reduced by zinc in acetic acid to give the dihydro product **17**. In the presence of D_2O and pyridine, the benzylic hydrogen in **17** is exchanged by deuterium, indicating that the 3*H*-benzofuran-2-one system readily enolizes.

Different from the previously reported reaction of DDQ with tetraalkyl-substituted oxepinobenzofurans **5a,b** leading to 3*H*-benzofuran-2-ones **13**, the oxidation of

Scheme II. Oxidative Conversions of Oxepinobenzofurans 5 into Benzofuranylidenones 14-16

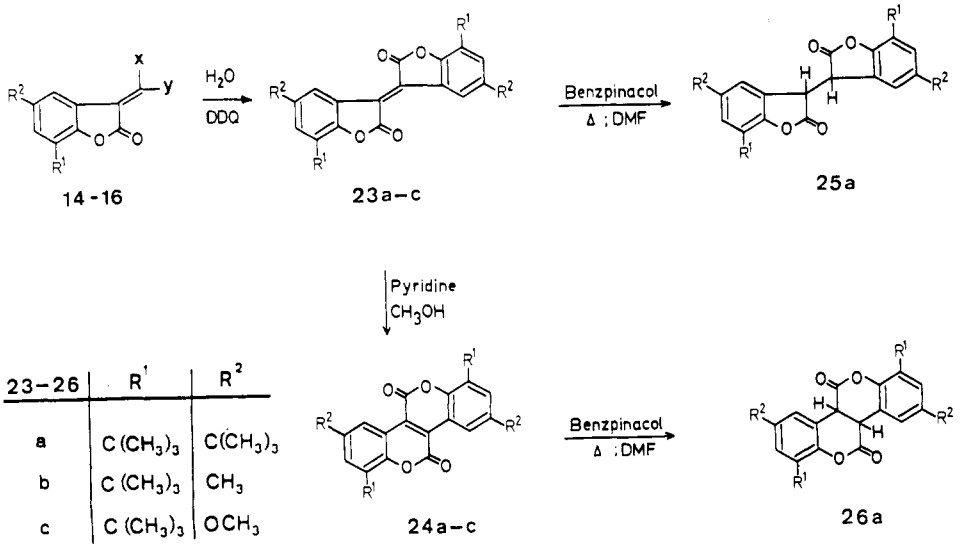


methoxy-substituted **5c** with 1 molar equiv of DDQ gives rise to the linearly conjugated benzofuranylidenone **15**. A common prerequisite for the oxidation of **5a–c** by DDQ is the presence of water. We believe, therefore, that the hydrolytic opening of the oxepino ring system, conceivably catalyzed by DDQ, is the primary step in a sequence of reactions (see Scheme II) leading to either furanyl-substituted benzofuranones **13** or to benzofuranylidenone **15**. The formation of **15** then appears readily explicable in terms of a straightforward dehydrogenation by DDQ of the hydrolysis product **18**. As for the formation of furanyl-substituted benzofuranones **13**, we assume that a 1,3 hydrogen shift efficiently competes with the straightforward dehydrogenation of **18** when R^2 is an alkyl substituent and that the formation of the furanyl moiety involves the addition of water to the exocyclic double bond in the rearrangement product **19**. The recently reported[15] conversion of 1,4-dihydroxybutanes by DDQ to give furans leads support to the proposed reaction sequence **23** → **21** → **22** → **13**. The conversion of **13** into **14** has been verified experimentally.[6]

In order to obtain experimental evidence for the assumption that water can be added to the exocyclic double bond of 3-benzofuranyliden-2-ones to give 3*H*-benzofuran-2-ones such as **20**, we investigated the reaction of benzofuranylidenones **14a,b** and **16** with DDQ in aqueous dioxane. In all three cases, dehydrogenation was found to proceed smoothly at elevated temperature. To our surprise, the resulting products were not the conceivable benzofuranone dehydro dimers[16] but the previously unknown isoxindigos **23**. Their formation from benzofuranylidenones **14–16** was found to require 2 molar equiv of DDQ, the presence of water was necessary, and yields of isoxindigos were then around 80% (Scheme III). Un-

(11) Hewgill, F. R.; Hewitt, D. G.; Howie, G. B.; Spencer, W. L. *Aust. J. Chem.* **1977**, *30*, 1971.
(12) Hewgill, F. R.; Hewitt, D. G.; Howie, G. B.; Raston, C. L.; Webb, R. J.; White, A. H. *J. Chem. Soc., Perkin Trans. 1* **1979**, 290.
(13) Hall, S. R.; Raston, C. L.; White, A. H. *Aust. J. Chem.* **1977**, *30*, 1978.
(14) Hall, S. R.; Raston, C. L.; White, A. H. *Aust. J. Chem.* **1977**, *30*, 1979.
(15) Becker, H.-D.; Björk, A.; Adler, E. *J. Org. Chem.* **1980**, *45*, 1596.
(16) Wasserman, H. H.; Liu, T.-C.; Wasserman, E. R. *J. Am. Chem. Soc.* **1953**, *75*, 2056. Cf. also: Mustafa, A. *Chem. Heterocycl. Comp* **1974**, *29*, 267. Bernatek, E.; Berner, E. *Acta Chem. Scand.* **1949**, *3*, 1117.

Scheme III



23-26	R¹	R²
a	$C(CH_3)_3$	$C(CH_3)_3$
b	$C(CH_3)_3$	CH_3
c	$C(CH_3)_3$	OCH_3

substituted isoxindigo had previously been obtained by condensation of coumaran-2,3-dione with coumaran-2-one.[17,18] As observed for the parent isoxindigo,[17,18] substituted isoxindigos **23** smoothly isomerize in pyridine solution to give the corresponding dibenzonaphthyrones **24**. The ^1H NMR data of **23** and **24**, summarized in Table I, are in agreement with the assigned trans structures.[19] We have also found during the course of this investigation that isoxindigos **23** and dibenzonaphthyrones **24** are easily converted into their corresponding dihydro derivatives **25** and **26** by hydrogen atom transfer from thermally generated diphenylhydroxymethyl radicals.[20] The reduction is accomplished simply by heating equimolar amounts of **23**/**24** and benzpinacol in dimethylformamide.[21]

As for the mechanism of isoxindigo formation from benzofuranylidenones **14–16**, we originally believed that the hydration product **27** was oxidatively dimerized by DDQ and that dihydroisoxindigos **25**, formed by retro-aldol reaction, were the precursors of isoxindigos **23**. However, an attempt to oxidatively dimerize 5,7-di-*tert*-butyl-2-(3*H*)-benzofuranone[22] by DDQ was unsuccessful insofar as only traces of tetra-*tert*-butylisoxindigo (**23a**) were formed. Likewise, we find that dihydroisoxindigo **25a** undergoes oxidation by DDQ in boiling dioxane rather sluggishly. Consequently, we assume the final step in the isoxindigo formation to involve an elimination rather than a dehydrogenation reaction. One conceivable route to isoxindigos by oxidative conversion of benzofuranylidenones is outlined in Scheme IV. We suggest that the hydration product **27**, or its enol, undergoes oxidative addition to DDQ and that the side chain of the benzofuranone moiety is lost by retro-aldol reaction.[23,24] Oxidative addition of the resulting enol **29** to **27** will lead to the coupling product **30** from which isoxindigos **23** may be formed by way of a retro-aldol/elimination reaction. Support for this mode of isoxindigo formation was obtained in the synthesis of **23a** from **14a** which concomitantly afforded a product for which spectroscopic and analytical data are in agreement with a compound of

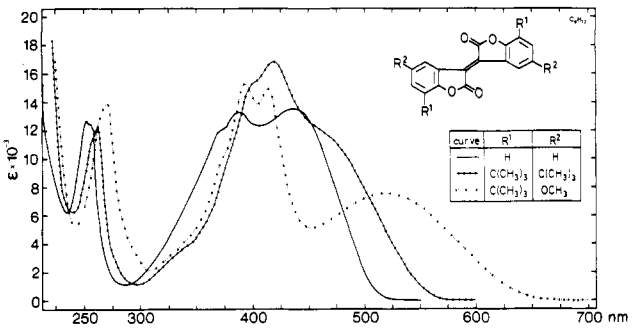


Figure 2. Electronic absorption spectra of isoxindigo and its derivatives **23a** and **23c** in cyclohexane. (The absorption spectrum of **23b** is superimposable with that of **23a**.)

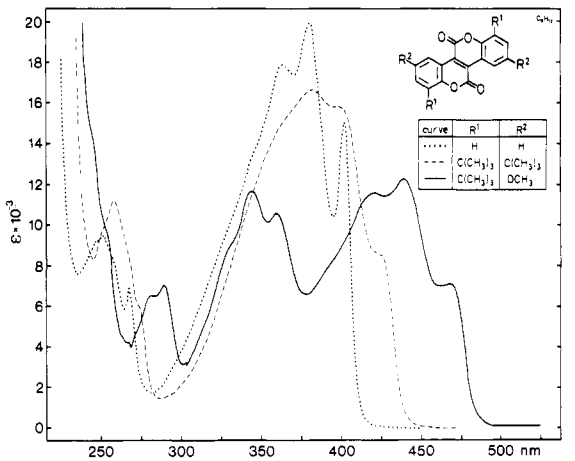
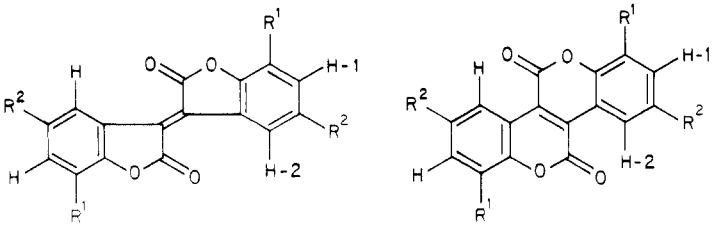


Figure 3. Electronic absorption spectra of dibenzonaphthyrone and its derivatives **24a** and **24c** in cyclohexane. (The spectra of **24a** and **24b** are virtually superimposable.)

(17) Chovin, P. *Bull. Soc. Chim. Fr.* **1944**, *11*, 82.
(18) Chatterjea, J. N. *J. Indian Chem. Soc.* **1959**, *36*, 69.
(19) X-ray structure analyses have been carried out on the parent isoxindigo, substituted isoxindigos **23a–c**, the parent dibenzonaphthyrone, and substituted dibenzonaphthyrones **24a–c**. We are currently evaluating the effects of substitution on the molecular geometry: Becker, H.-D.; White, A. H. et al., to be submitted for publication.
(20) Dihydroisoxindigos may exist in diastereoisomeric meso and racemic forms. According to its ^1H NMR spectrum, **25a** is stereochemically uniform. As the hydrogen atom transfer mechanistically involves stepwise reduction of the ene–dione system (see ref 21), we believe we have prepared the meso form of **25a**. By contrast, cis hydrogenation of the ene double bond would give the racemic form of **25a**. In line with these considerations, we find that **25a** in the presence of pyridine exists as a mixture of isomers (^1H NMR). We expect the meso form to undergo base-catalyzed racemization quite easily. As for the dihydro product **26a**, we assume the compound to be the trans isomer.
(21) Becker, H.-D. *J. Org. Chem.* **1969**, *34*, 2472. Becker, H.-D.; Sanchez, D.; Arvidsson, A. *Ibid.* **1979**, *44*, 1979.
(22) Becker, H.-D.; Gustafsson, K. *J. Org. Chem.* **1977**, *42*, 2966.
(23) Becker, H.-D. *J. Org. Chem.* **1965**, *30*, 989.
(24) The formation of a $DDQH_2$ mono ether by reaction of DDQ with an enolizable ketone has been found previously.[23]

Table I. ^{1}H NMR Spectral Data of Isoxindigos (A) and Dibenzonaphthyrones (B)

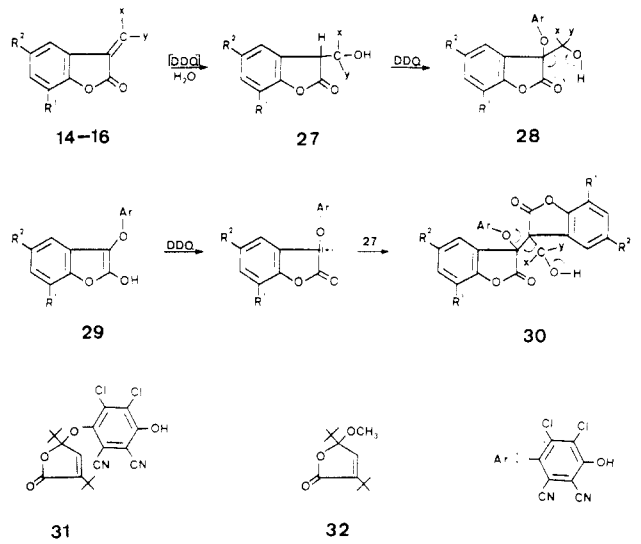


A B

			shift, δ (multiplicity)				
	R^1	R^2	H-1	H-2	R^1	R^2	J (Hz)
A	H	H	7.54 (t)	9.10 (d)	7.17 (d)	7.27 (t)	8,[a] 1[b]
	$C(CH_3)_3$	CH_3	7.25 (s)[c]	8.73 (s)[c]	1.43 (s)	2.40 (s)[c]	
	$C(CH_3)_3$	$C(CH_3)_3$	7.51 (d)	9.08 (d)	1.45 (s)	1.39 (s)	2
	$C(CH_3)_3$	OCH_3	7.07 (d)	8.58 (d)	1.42 (s)	3.88 (s)	3
B	H	H	7.65 (t)	9.26 (d)	7.43 (d)	7.44 (t)	8,[a] 1[b]
	$C(CH_3)_3$	CH_3	7.41 (d)[d]	8.96 (d)[d]	1.54 (s)	2.47 (s)[d]	2
	$C(CH_3)_3$	$C(CH_3)_3$	7.68 (d)	9.25 (d)	1.57 (s)	1.41 (s)	2
	$C(CH_3)_3$	OCH_3	7.24 (d)	8.76 (d)	1.54 (s)	3.93 (s)	3

[a] Ortho coupling. [b] Meta coupling. [c] Broad. [d] Allylic coupling <1 Hz.

Scheme IV. Oxidative Formation of Isoxindigos from Benzofuranylidenones



14–16 27 28 29 30 31 32

structure **31**. Its formation, rather than that of the expected retro-aldol reaction product **32**, is explicable by a transesterification reaction.[25]

We have deemed it of particular interest to study the electron spectral properties of isoxindigos and those of their isomeric dibenzonaphthyrones since the two chromophores in question differ "merely" in the conformational arrangement of the central ene–dione system. An indigoid chromophore has been recognized to have an electron accepting ene–dione moiety in the trans-*s*-cis-*s*-cis conformation substituted by an electron donor moiety X, as shown in Scheme V.[26-28] We find the longest wavelength absorption of the parent isoxindigo around 437 nm to be structureless, as is in agreement with the charge-transfer concept for an indigoid chromophore. By contrast, the ene–dione system of dibenzonaphthyrones is in the trans-*s*-trans-*s*-trans arrangement, and the longest wavelength absorption of the parent compound is hypsochromically shifted with respect to that of isoxindigo and is characterized by fine structure (see Figures 2 and 3).

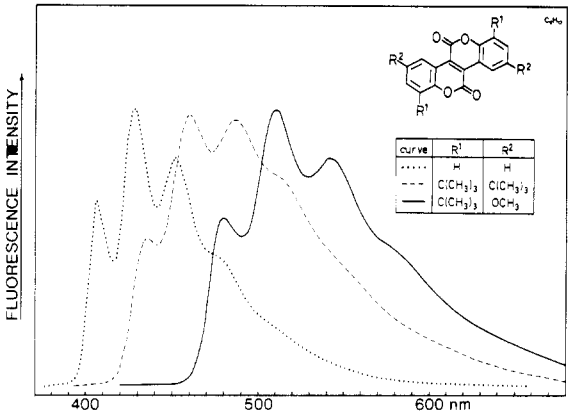


Figure 4. Fluorescence spectra of dibenzonaphthyrones.

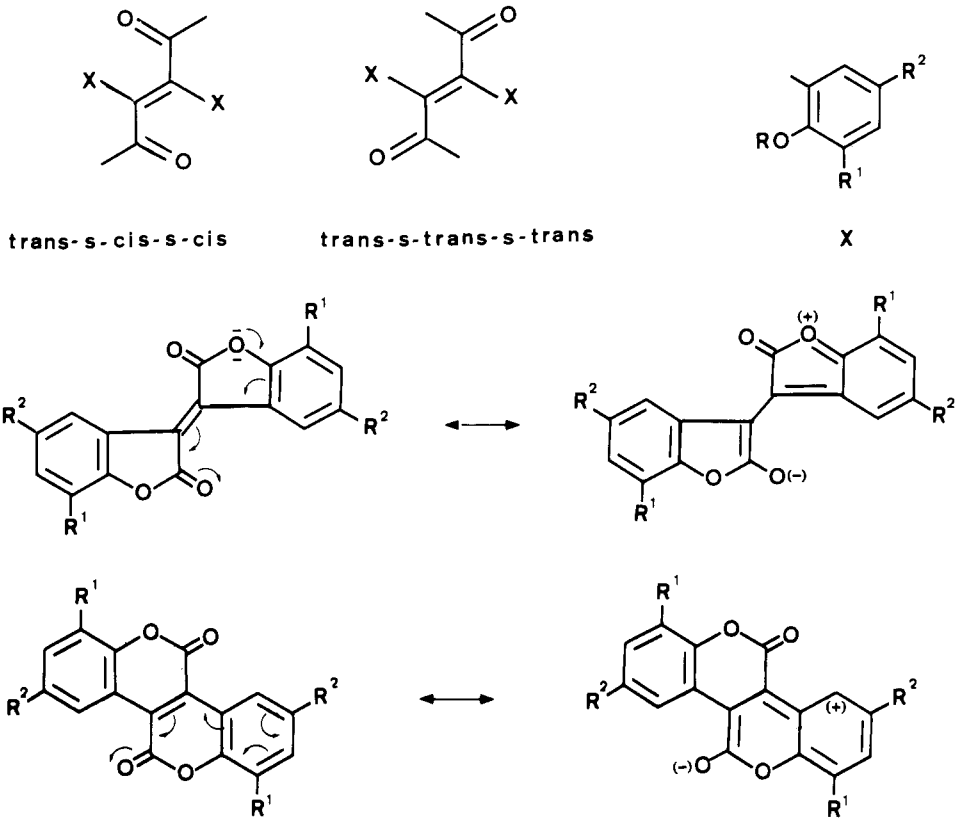
The effect of substitution on the color of isoxindigos was found to be truly dramatic. In the crystalline state, the parent compound is golden yellow, tetraalkyl-substituted isoxindigos **23a** and **23b** are deep red, and the methoxy-substituted isoxindigo **23c** is black. Inspection of the solution spectra reveals the deep color of methoxy-substituted isoxindigo to have its origin in a broad charge-transfer absorption, with a maximum around 525 nm, which is well separated from a π–π^* transition around 400 nm common to all isoxindigos described in this paper. Thus, the effect of substitution appears to be such as to lower the energy of the charge-transfer absorption of isoxindigos, and it is the methoxy group which greatly enhances the electron donor properties of the substituent X (cf. Scheme V).

As for the absorption spectra by dibenzonaphthyrones **24a–c**, the bathochromic shift induced by substitution follows the same order as that noted for isoxindigos **23**. However, the longest wavelength absorption in the spectra of dibenzonaphthyrones always retains its fine structure. Furthermore, characteristically different from isoxindigos, dibenzonaphthyrones are fluorescent. Interestingly, the structural relationship between substituted dibenzonaphthyrones, hardly deducible from a comparison of their absorption spectra, is readily apparent in the striking

(25) We have previously shown that pseudoester **14a**, then believed to be pseudoester **12**, can undergo transesterification (cf. ref 6).

(26) Klessinger, M.; Lüttke, W. *Tetrahedron Suppl.* **1963**, *No. 2*, 315. Luhmann, U.; Lüttke, W. *Chem. Ber.* **1978**, *111*, 3246 and references therein.
(27) Ammon, H. L.; Hermann, H. *J. Org. Chem.* **1978**, *43*, 4581.
(28) Cf. also: Dähne, S. *Z. Chem.* **1981**, *21*, 58.

Scheme V. Effect of Enedione Conformation on the Charge-Transfer Resonance Structures of Isoxindigos and Dibenzonaphthyrones



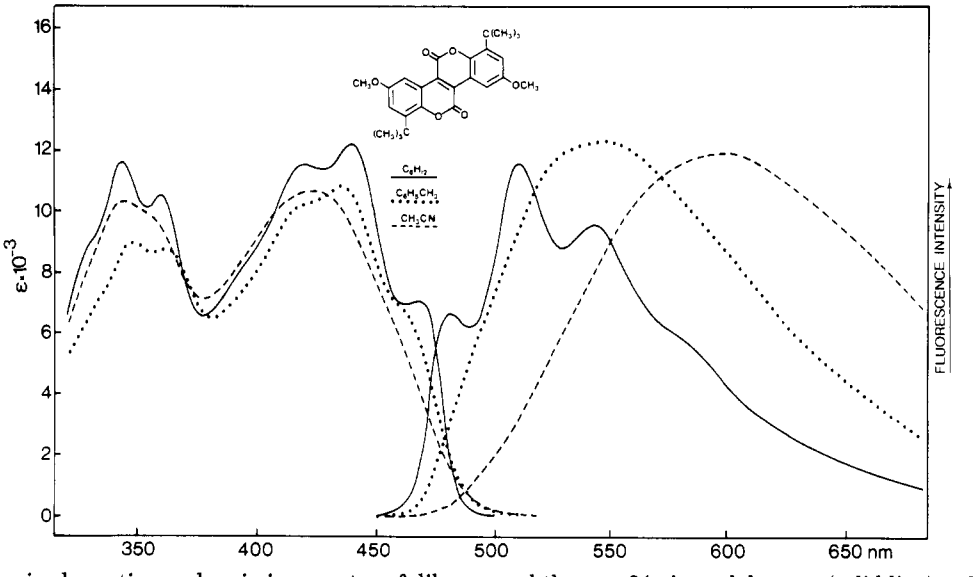


Figure 5. Electronic absorption and emission spectra of dibenzonaphthyrone **24c** in cyclohexane (solid line), toluene (dotted line), and acetonitrile (dashed line).

similarity of their emission spectra (see Figure 4). In cyclohexane solution, the fluorescence spectra are structured, and they are characterized by small Stokes shifts. Quantum yields vary between 2% for **24a** and **24b**, 5% for the parent compound, and 10% for **24c**.[29] Dipolar contributions to the electronic ground state and to the emitting state of dibenzonaphthyrones become important in solvents of higher dielectric constant, as we conclude from the solvent dependence of their absorption and emission spectra. For example, in the absorption spectrum of **24c** in acetonitrile solution, virtually all fine structure has been lost due to band broadening (see Figure 5).

The emission spectrum of **24c** in acetonitrile also is structureless and, significantly, the emission maximum red-shifted. Apparently, the lowest excited state of dibenzonaphthyrones is more polar in character (cf. Scheme V) than is the electronic ground state. It is in this latter respect that the dibenzonaphthyrone chromophore differs from that of isoxindigos which is characterized by ground-state charge-transfer interaction between the two molecular halves.

(29) Quantum yields are based on the fluorescence quantum yield of 9,10-diphenylanthracene (ϕ = 0.83). We are indebted to Dr. K. Sandros for these measurements.

Experimental Section

Melting points were taken on a hot-stage microscope and are

not corrected. IR spectra were recorded on a Beckman IR spectrometer, Model IR 9. Electronic absorption and emission were obtained on a Beckman Acta III spectrophotometer and an Aminco SPF 500 (corrected spectra) spectrofluorometer, respectively. ^1H NMR spectra were obtained on a Bruker 270 instrument, and chemical shifts are given in parts per million downfield from Me_4Si.

Materials. DDQ was recrystallized from methylene chloride. The oxidation of 2-*tert*-butyl-4-methoxyphenol with potassium ferricyanide to give **5c** was carried out as described by Baltes and Volbert.[30] Isoxindigo and dibenzonaphthyrone were prepared as described in the literature.[17,18]

Oxidation of 5c with DDQ in Aqueous Methanol To Give 15. DDQ (908 mg, 4 mmol) was added rapidly[31] to a deep blue stirred suspension of **5c** (1.42 g; 4 mmol) in methanol (12 mL) containing 3 drops of water. The reaction mixture immediately formed a deep red solution, and within 2 or 3 min an orange precipitate formed. The reaction mixture was diluted with about 3 mL of water, and the precipitate was removed by filtration and washed with aqueous methanol (~1:1): yield 600 mg (40%); orange crystals; mp 130–134 °C; ^1H NMR ($CDCl_3$) 1.21 (s, 9, *tert*-butyl), 1.39 (s, 9, *tert*-butyl), 3.82 (s, 3, methoxy), 3.84 (s, 3, methoxy), 6.79 (d, J = 2.5 Hz, 1 arom H), 6.82 (s, 1), 6.91 (d, J = 2.5 Hz, 1 arom H), 6.96 (s, 1); IR (KBr) 1770 cm^{-1} (CO). Anal. Calcd for $C_{22}H_{28}O_5$ (mol wt 372.44): C, 70.94; H, 7.58. Found: C, 71.30; H, 7.58.

Upon being heated in solution or in the solid state, **15** smoothly dimerizes to give a colorless product, mp 243–245 °C. This dimerization involves the Diels–Alder addition of the exocyclic double bond to the cis–diene system. We are currently engaged in elucidating the molecular geometry of this dimer by X-ray diffraction.

Acid-Catalyzed Isomerization of 15 To Give 16. A puff of hydrogen chloride gas was added to a solution of **15** (50 mg) in methylene chloride (3 mL). The solution immediately turned lighter in color. Vacuum evaporation of solvent gave **16** (quantitatively), mp 187–189 °C (no depression upon admixture of **16** obtained by DDQ oxidation in aqueous dioxane).

Oxidation of 5c with DDQ in Aqueous Dioxane To Give 16. DDQ (2.27 g, 10 mmol) was added to a stirred suspension of **5c** (3.56 g, 10 mmol) in dioxane (50 mL) containing water (2 mL). $DDQH_2$ started precipitating immediately as the blue suspension turned orange. After 10 min, the reaction mixture was diluted with CH_2Cl_2 (30 mL), and $DDQH_2$ (2.08 g) was removed by filtration. Vacuum evaporation of solvents left an oily residue which crystallized upon addition of methanol (15 mL). The crystalline product (2.96 g, mp 170–180 °C) was recrystallized from CH_2Cl_2 by addition of methanol and boiling off part of the solvent: yield 2.80 g (77%); mp 189–191 °C (lit.[8] mp 189.5–191 °C); ^1H NMR ($CDCl_3$) 1.22 (s, 9, *tert*-butyl), 1.38 (s, 9, *tert*-butyl), 3.81 (s, 3, methoxy), 3.92 (s, 3, methoxy), 6.11 (s, 1), 6.90 (d, J = 2.5 Hz, 1 arom H), 7.18 (d, J = 2.5 Hz, 1 arom H), 8.09 (s, 1); IR (KBr) 1770 cm^{-1} (CO). Anal. Calcd for $C_{22}H_{28}O_5$ (mol wt 372.44): C, 70.94; H, 7.58. Found: C, 71.14; H, 7.32.

Reduction of 16 by Zinc in Acetic Acid To Give 17. Acetic acid (25 mL) was added to a mixture of **16** (1 g) and zinc powder (2.5 g). The stirred reaction mixture was kept in a bath at 55–65 °C for 10 min. Filtration gave a pale yellow filtrate which gave a colorless crystalline precipitate upon addition of water: yield 960 mg (95%); mp 119–121 °C. Recrystallization from aqueous methanol raised the melting point to 122–123 °C (lit.[8] mp 121.5–123 °C): ^1H NMR (C_6D_6) 1.06 (s, 9, *tert*-butyl), 1.34 (s, 9, *tert*-butyl), 2.89 (s, 3, methoxy), 3.21 (dd, J_{AB} = 15 Hz, J_{BX} = 4 Hz, 1, H_B), 3.37 (s, 3, methoxy), 3.49 (dd, J_{AX} = 7.5 Hz, J_{BX} = 4 Hz, 1, benzylic H_X), 3.99 (dd, J_{AB} = 15 Hz, J_{AX} = 7.5 Hz, 1, H_B), 5.38 (s, 1, methine), 6.6 (dd, J_{meta} = 1.5 Hz, long-range coupling with H_X = 0.5 Hz, 1 aromatic H), 6.80 (d, J_{meta} = 1.5 Hz, 1 aromatic H); IR (KBr) 1790 cm^{-1} (CO). Anal. Calcd for $C_{22}H_{30}O_5$ (mol wt 374.46): C, 70.60; H, 8.07. Found: C, 70.82; H, 8.10.

Compound 17 by Reduction of 15 with Zinc in Acetic Acid. Acetic acid (5 mL) was added to a mixture of **15** (100 mg) and zinc powder (1.2 g). The stirred reaction mixture was kept at 45 °C for 2 min. A workup by filtration and evaporation of solvents from the filtrate gave a residue which was recrystallized from aqueous methanol to give colorless crystals: yield 55 mg; mp 120–122 °C. The melting point was not depressed upon admixture of **17** obtained from **16**.

Tetra-*tert*-butylisoxindigo 23a. A solution of **14a** (1.8 g, 4 mmol) and DDQ (1.8 g, 8 mmol) in a mixture of dioxane (16 mL) and water (2 mL) was refluxed for 75 min. Vacuum evaporation of solvents from the deep red reaction mixture gave a dark-colored residue which was washed with methylene chloride (100 mL) to leave 720 mg of $DDQH_2$ undissolved. Evaporation of solvent from the filtrate gave a deep red crystalline residue which was triturated with methanol to give 750 mg (77%) of **23a** as bright red crystals, mp 252–253 °C. Recrystallization by dissolving the crystals in methylene chloride and adding methanol raised the melting point to 253–255 °C; IR (KBr) 1770 cm^{-1}. Anal. Calcd for $C_{32}H_{40}O_4$ (mol wt 488.67): C, 78.65; H, 8.25. Found: C, 78.47; H, 8.32.

Evaporation of solvent from the methanol filtrate obtained after isolation of **23a** gave a deep dark red oily residue which was dissolved in about 10 mL of ether. After 1 day at room temperature, a colorless crystalline precipitate had formed which was removed by filtration and recrystallized by precipitation with water from methanol solution: yield 1.4 g; needle-shaped crystals; mp >120 °C dec; IR (KBr) 1762 (CO), 2120 (CN), 3480, 3550 cm^{-1} (OH); ^1H NMR ($CDCl_3$) 1.11 (s, 9, *tert*-butyl), 1.24 (s, 9, *tert*-butyl), 7.22 (s, 1), very broad absorption around 3.5 (attributed to OH). The elemental analysis of this product is in agreement with a hydrate of **31**. Anal. Calcd for $C_{20}H_{20}Cl_2N_2O_4 \cdot H_2O$: C, 54.43; H, 5.02. Found: C, 54.83; H, 4.87. After 3 h at 100 °C (0.03 torr) over P_2O_5, the analysis showed the following: C, 56.00; H, 4.36. Anal. Calcd for $C_{20}H_{20}Cl_2N_2O_4$: C, 56.75; H, 4.76.

Di-*tert*-butyldimethylisoxindigo 23b. A solution of **14b** (1.42 g, 4 mmol) and DDQ (1.82 g, 8 mmol) in dioxane (16 mL) containing water (2 mL) was refluxed for 60 min. A workup as described for **23a** gave 550 mg (70%) of bright red needle-shaped crystals: mp 250–251 °C; IR (KBr) 1780 cm^{-1}. Anal. Calcd for $C_{26}H_{28}O_4$ (mol wt 404.51): C, 77.20; H, 6.98. Found: C, 76.80; H, 6.94.

Di-*tert*-butyldimethoxyisoxindigo 23c. A stirred suspension of **16** (744 mg, 2 mmol) and DDQ (908 mg, 4 mmol) in dioxane (8 mL) and water (1 mL) was refluxed for 1 h. $DDQH_2$ precipitated as the lactone dissolved. Filtration after addition of CH_2Cl_2 (100 mL) gave $DDQH_2$ (660 mg). Evaporation of solvent from the deep purple filtrate left a black crystalline residue which was recrystallized from CH_2Cl_2 by addition of methanol: yield 374 mg (86%); mp 245–250 °C; IR (KBr) 1770 cm^{-1}. Anal. Calcd for $C_{26}H_{28}O_6$ (mol wt 436.51); C, 71.54; H, 6.47. Found: C, 71.20; H, 6.44.

Isomerization of Tetra-*tert*-butylisoxindigo 23a in Pyridine To Give 24a. The deep red solution of **23a** (500 mg) in a mixture of pyridine (25 mL) and methanol (25 mL) was refluxed for 15 min. By then the solution had turned bright yellow. Vacuum evaporation of solvents left a yellow crystalline residue which was washed with methanol to give **24a**: 495 mg (95%); bright yellow crystals; mp 245–246 °C. Recrystallization from a boiling mixture of methylene chloride and methanol did not change the melting point; IR (KBr) 1730 cm^{-1}. Anal. Calcd for $C_{32}H_{40}O_4$ (mol wt 488.67): C, 78.65; H, 8.25. Found: C, 78.83; H, 8.32.

Isomerization of Di-*tert*-butyldimethylisoxindigo 23b To Give 24b. The isomerization of **23b** was carried out in the same fashion as described for **23a**. Recrystallization from CH_2Cl_2/CH_3OH gave bright yellow crystals: mp 287–289 °C; IR (KBr) 1720 cm^{-1}. Anal. Calcd for $C_{26}H_{28}O_4$ (mol wt 404.51): C, 77.20, H, 6.98. Found: C, 76.95; H, 6.95.

Isomerization of Di-*tert*-butyldimethoxyisoxindigo 23c To Give 24c. A solution of **23c** (400 mg) in a mixture of pyridine (25 mL) and methanol (25 mL) was refluxed for 2 h. Vacuum evaporation of solvent gave a yellow crystalline residue which was recrystallized from methylene chloride by addition of methanol:

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(31) It is essential to add the DDQ rapidly to the suspension of the 2,2′-diphenoquinone isomer **5c**. Slow addition of DDQ over a 15-min period gives mainly 1,1′-bicyclohexa-1,4-diene-3,3′,6,6′-tetrone which precipitates from the solution in 50% yield. Other products, identified by TLC, were 4,6-di-*tert*-butyl-8-methoxydibenzofuran-1,2-quinone, and 4,6-di-*tert*-butyl-1,2,8-trimethoxydibenzofuran. Apparently, valence isomer **5c** equilibrates slowly, and the formation of the tetrone is indicative of the presence of other valence isomers undergoing nucleophilic addition of water.

yield 390 mg (97%); yellow crystals; mp 305–306 °C. Anal. Calcd for $C_{26}H_{28}O_6$ (mol wt 436.51): C, 71.54; H, 6.47. Found: C, 71.93; H, 6.51.

Reduction of Tetra-*tert*-butylisoxindigo with Benzpinacol To Give 25a. A solution of **23a** (976 mg, 2 mmol) and benzpinacol (732 mg, 2 mmol) in DMF (10 mL) was heated under nitrogen to reflux temperature whereupon the deep red solution turned colorless. Addition of aqueous methanol at room temperature gave a colorless crystalline precipitate which was removed by filtration and washed with petroleum ether: yield 720 mg (73%); mp 162–165 °C. Recrystallization by dissolving in ether and precipitation with petroleum ether (bp 40–60 °C) did not change the melting point: ^{1}H NMR ($CDCl_3$) 1.20 (s, 9), 1.36 (s, 9), 4.45 (s, 1), 6.66 (d, J = 2 Hz, 1), 7.32 (d, J = 2 Hz, 1); IR (KBr) 1810 cm^{-1}. Anal. Calcd for $C_{32}H_{42}O_4$ (mol wt 490.69): C, 78.33; H, 8.63. Found: C, 78.38; H, 8.75.

Reduction of Tetra-*tert*-butyl-dibenzonaphthyrone 24a with Benzpinacol To Give 26a. A solution of **24a** (224 mg, 0.5 mmol) and benzpinacol (201 mg, 0.55 mmol) in DMF (4 mL) was heated under nitrogen to reflux temperature to give a colorless solution. Dilution of **Tetra-*tert*-butyldibenzonaphthyrone** reaction mixture with water and methanol gave a colorless crystalline precipitate of **26a**: 220 mg (90%); mp 210–211 °C; recrystallization from aqueous methanol did not change the melting point; ^{1}H NMR ($CDCl_3$) 1.2 (s, 9), 1.35 (s, 9), 4.43 (s, 1), 7.05 (d, J = 2 Hz, 1), 7.26 (d, J = 2 Hz, 1); IR (KBr) 1770 cm^{-1}. Anal. Calcd for $C_{32}H_{42}O_4$ (mol wt 490.69): C, 78.33; H, 8.63. Found: C, 78.25; H, 8.71.

Registry No. 5c, 65905-73-9; (*E*)-**14a**, 80360-46-9; (*E*)-**14b**, 66737-81-3; (*Z,Z*)-**15**, 64309-44-0; (*E,E*)-**16**, 64309-45-1; **17**, 64675-30-5; (*E*)-**23** ($R^1 = R^2$ = H), 80360-47-0; (*E*)-**23a**, 75540-64-6; (*E*)-**23b**, 80360-48-1; (*E*)-**23c**, 80360-49-2; **24** ($R^1 = R^2$ = H), 13225-81-5; **24a**, 80360-50-5; **24b**, 80360-51-6; **24c**, 80360-52-7; *meso*-**25a**, 80360-53-8; *dl*-**25a**, 80360-54-9; *trans*-**26a**, 80360-55-0; **31**, 80360-56-1; DDQ, 84-58-2.

New Synthesis of α-Benzoyloxy Aldehydes. Application to the Stereoselective Synthesis of Conjugated (*E,E*)-Dienoic Esters[1]

Takashi Sakai, Katsuhiko Seko, Akihiro Tsuji, Masanori Utaka, and Akira Takeda*

Department of Synthetic Chemistry, School of Engineering, Okayama University, Tsushima, Okayama 700, Japan

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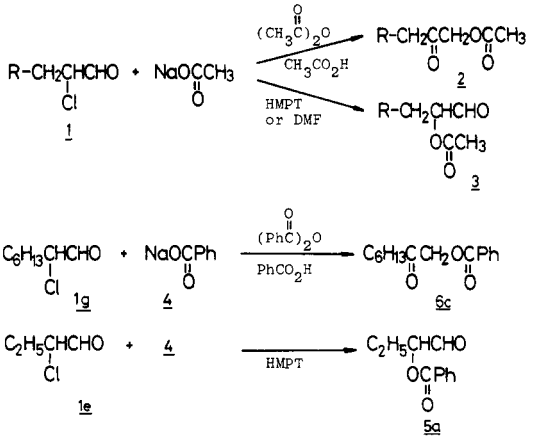
A new synthetic method for the preparation of secondary α-benzoyloxy aldehydes (**5a–d**) and its use in the stereoselective synthesis of conjugated (*E,E*)-dienone (**14**) and dienoic esters (**9b, 9c, 11, 15b,** and **15c**) were studied. Two-phase (benzene–H_2O) reaction of $RCH_2CHXCHO$ (R = CH_3, C_3H_7, C_5H_{11}, C_7H_{15}; X = Cl, Br) with sodium benzoate (**4**) in the presence of a catalytic amount of tetrabutylammonium bromide gave the corresponding α-benzoyloxy aldehydes (**5a–d**) in moderate yields. Compounds **5a–d** were converted to γ-benzoyloxy-α,β-unsaturated carbonyl compounds or esters (**7b, 7c, 10, 12, 13b,** and **13c**) either by the $TiCl_4$/py-catalyzed condensation with malonate or acetoacetate or by the Wittig reaction with $Ph_3P{=}CHC(O)CH_3$ and $Ph_3P{=}CHCO_2Et$. Treatment of these compounds with 5 mol % of $(Ph_3P)_4Pd$ in refluxing THF afforded the corresponding conjugated (*E,E*)-dienones and dienoic esters stereoselectively. The reaction sequence was further extended to the stereoselective synthesis of ethyl (2*E*,4*E*,6*E*)-2,4,6-dodecatrienoate (**18**) and pellitorine (**21**).

α-Acyloxy aldehydes are important class of starting materials for the synthesis of heterocycles such as furans[2] and γ-butyrolactones.[3] The known methods of α-acyloxy aldehyde synthesis are as follows: (a) the hydroformylation (CO/H_2) of 1-alkenyl acetates,[4a] (b) the acylation of 2-(α-hydroxyalkyl)-1,3-dithianes,[4b] (c) the oxidative cleavage of aldehydes[4c] or glycidates[5a] with lead tetraacetate, (d) the reaction of silyl enol ethers with lead tetrabenzoate,[4d] (e) the reaction of α-chloro aldehydes with sodium acetate in polar, aprotic solvents,[4e] (f) the reaction of tertiary α-bromo aldehydes with potassium phenylacetate in the presence of 18-crown-6.[5b]

Scheme I



In this paper we report a simple and convenient procedure for the preparation of α-benzoyloxy aldehydes, which involves the reaction of an α-halo aldehyde (**1**) with sodium benzoate (**4**) in a two-phase system consisting of

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