

Photosensitized Oxidation of Furans. Part 7.¹ Solvent Effects in Thermal Conversion of the *endo*-Peroxides of Arylfurans

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Thermal conversion of the *endo*-peroxides of the arylfurans (1) in a polar aprotic solvent leads to aroylenol esters (4) and diaroyl epoxides (3), the predominance of one over the other being concentration dependent. The results can be rationalized on the basis of the intermediacy of dipolar species, *e.g.* (6a) and/or (7a-d), which are formed in the first stages of the reaction and can react intra- and/or inter-molecularly. The behaviour of the peroxides (1) in an apolar solvent suggests that in this case the epoxides (3) are predominantly formed by a different route, probably involving an intramolecular synchronous rearrangement.

The synthesis, the isolation, and the chemical behaviour of the *endo*-peroxides of substituted furans have been the subject of recent investigations;¹⁻⁶ these have allowed the elucidation of ambiguities associated with the photosensitized oxidation of furans.⁷ In order to gain more mechanistic insight into the thermal reactions of this class of bicyclic peroxides, we have now investigated the dynamic chemistry of the epidioxy-diaryldihydrofurans in organic solvents.

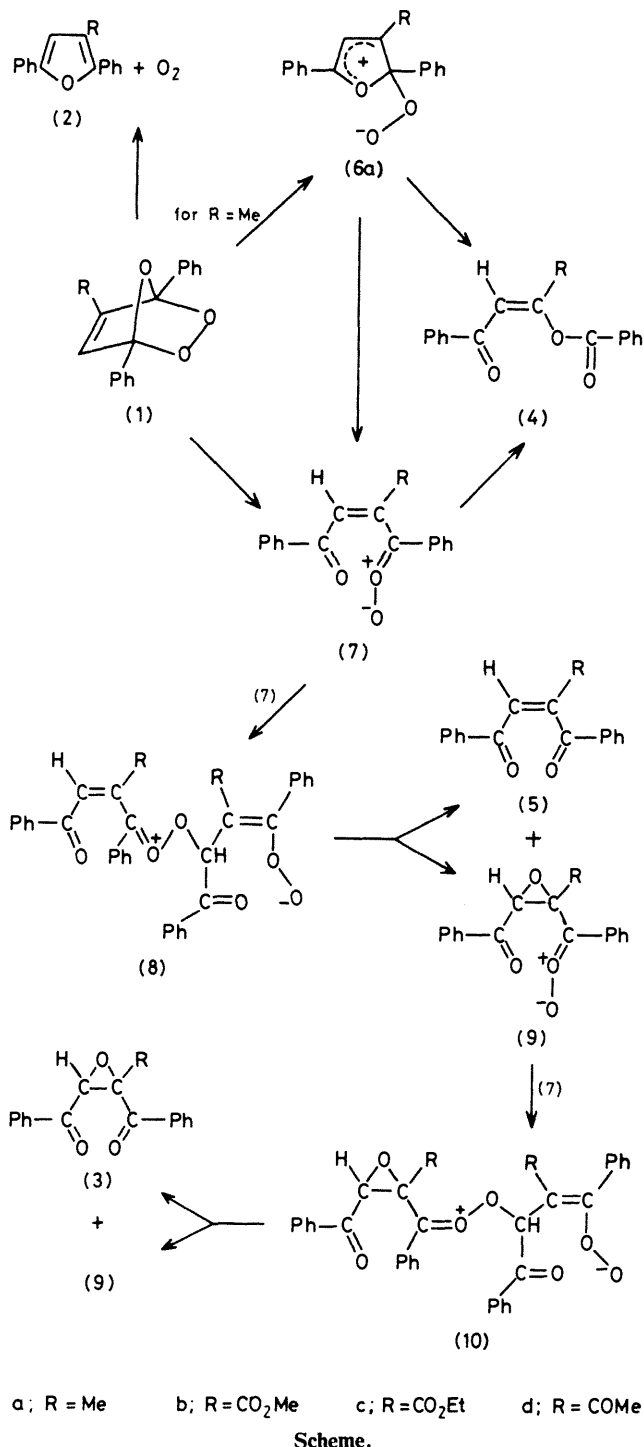
We reported that the *endo*-peroxides of 2,5-diarylfurans such as (1), in carbon tetrachloride at 4 °C, lead to the parent furans (2) and *cis*-1,2-diaroyl epoxides (3) as major products and *cis*-2-aroylenol esters (4) and *cis*-1,2-diaroylethylenes (5) as minor products.⁵ The conversion into the parent furans and molecular oxygen either on the basis of the influence of the solvent polarity on the product distribution^{5,6} or by comparison with similar retro-[4 + 2]cycloadditions,⁸ must be considered as a concerted fragmentation or as a decomposition *via* an initial diradical intermediate. In contrast, the conversion into the enol esters (4) is explained in terms of a stepwise mechanism involving dipolar intermediates, such as (6) or (7).^{6,9} In particular, in dilute nitromethane solution the peroxides (1) rearrange to the esters (4) irrespective of the electron-donating or -attracting character of the β -substituent. Therefore we suggest that cyclic dipolar intermediates such as (6) with electron-donating β -substituents or, alternatively, acyclic carbonyl oxides (7) with electron-withdrawing β -substituents, are operative.⁶ In order to obtain information concerning the formation of the epoxides (3), we have undertaken experiments centred on intermolecular oxygen transfer from the carbonyl oxides (7) to the diaroylethylenes (5), as previously suggested for a tetraphenylfuran-singlet oxygen adduct.^{7c,†} In this connection account was taken of the fact that the intermediate (6) can easily collapse to the carbonyl oxide (7). Therefore the zwitterions (6) and/or (7) should be common intermediates for the esters (4) (intramolecular rearrangement) and epoxides (3) (intermolecular oxygen transfer). On the basis that an increase in concentration would ensure that the

rate of intermolecular reactions is enhanced, we have carried out the conversion of the peroxides (1a-d) in nitromethane at two different concentrations. In Table 1 the proportions of the conversion products in $15 \times 10^{-2}M$ and $2 \times 10^{-2}M$ solutions at 4 °C are reported. Quantification of the reaction products was made on the basis of the ¹H n.m.r. spectra of the reaction mixture and confirmed by chromatography on silica gel. The hitherto known compounds were identified by straightforward comparison of their i.r. and ¹H n.m.r. spectra with those of authentic samples. The structures of the new products were assigned on the basis of elemental analyses and spectral data summarized in Table 2. A series of nuclear Overhauser effect (n.O.e.) difference experiments and the ¹H n.m.r. solvent effect performed on *cis*- and *trans*-isomers¹¹ confirmed the *cis*-configuration of the epoxide (3), which could also be assigned on the basis of previous results.^{2,5}

The behaviour of the *endo*-peroxides (1a-d) provides evidence for the proposal that in a polar aprotic solvent at high concentration, dipolar intermediates, *e.g.* (7a-d), lead to the epoxides (3a-d) by oxygen transfer on species present in the reaction mixture. In order to examine the possibility that oxygen acceptors are the diaroylethylenes (5a-d),^{7c} thermal conversion of the peroxide (1c) in nitromethane was carried out in the presence of *cis*-3-benzoyl-1-phenylpent-2-ene-1,4-dione (5d). When the peroxide (1c) was completely transformed, the ¹H n.m.r. spectrum of the solution showed, in addition to the signals of the products deriving from thermal conversion of (1c), only the signals of the ethylene (5d); the epoxide (3d) was not detected. These data were confirmed by chromatography on silica gel. Similarly, when thermal conversion of the peroxide (1c) was carried out in nitromethane in the presence of *cis*-2-methyl-1,4-diphenylbut-2-ene-1,4-dione (5a), the epoxide (3a) was not detected. On the basis of these results it can be concluded that the ethylenes (5) are not intermediates in the reaction and, therefore, in our work, a mechanism as reported for a tetraphenylfuran-singlet oxygen adduct^{7c} must be discarded. Formation of the epoxides (3a-d) *via* intermolecular oxygen transfer from dipolar intermediates to still unchanged *endo*-peroxides (1a-d) may also be excluded. In fact, evidence contrary to this mechanism was obtained by investigating the crude nitromethane solution of equimolar quantities of peroxides (1a) and (1c), kept at 4 °C, soon after the signals of the compound (1a)† had disappeared in the ¹H n.m.r. spectrum. Inspection of this spectrum showed the peroxide (1c) to be completely unchanged. Furthermore, addition of diethyl sulphide¹

† Evidence for a carbonyl oxide intermediate was provided using diphenyl sulphide as a trapping agent; in the presence of this reagent no epoxide was formed and diphenyl sulphoxide was obtained.^{7c} The result was considered significant in that diphenyl sulphide was assumed to give no monodeoxygenation of 1,4-transannular peroxides.¹⁰ However, in a control experiment we have pointed out that there is significant direct attack of the diphenyl sulphide also on the dimethyl 2,5-epidioxo-2,5-dihydro-2,5-dimethylfuran-3,4-dicarboxylate. This *endo*-peroxide by thermal conversion at 77 °C leads quantitatively to diepoxide,^{4,5} undoubtedly with no formation of dipolar species. Therefore deoxygenation of the peroxides (1) by diphenyl sulphide does not give a clear-cut answer for the intermediate carbonyl oxides (7).

‡ As previously reported⁵ the peroxide (1a) is less stable than the *endo*-peroxides of furans substituted at position 3 with an electron-withdrawing group, *e.g.* (1c).

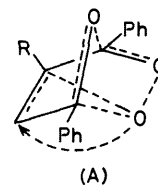


followed by silica gel chromatography afforded, in addition to the products deriving from thermal conversion of the peroxide (1a), only the diaroyl ethylene (5c). The epoxide (3c) * was not detected. It follows that, in nitromethane, intermolecular oxygen transfer can take place only between dipolar species, e.g. as shown in the Scheme. The fact that a *cis*-addition is actually involved could be interpreted in terms of a concerted addition of the carbonyl oxides (7) and (9) with

* Control experiments showed that the epoxide (3c) was not affected by diethyl sulphide.

synchronous formation of the two carbon-oxygen bonds on epoxidation. However, it is quite conceivable that the formation of the two bonds is nonsynchronous and that the second bond is formed at a rate greater than that of bond rotation in the intermediates (8) and (10). The mechanism reported in the Scheme also accounts for the recovery of a little of the diaroyl ethylenes (5) which can, at least partly, be formed when the intermediates (7) act as oxygen donors without undergoing mutual oxidation.

In order to gain more mechanistic insight, the thermal conversion of the peroxides (1a-d) at two different concentrations was carried out in apolar carbon tetrachloride † at 4 °C. The results, which are summarized in Table 1, show that the furans (2a-d) and the epoxides (3a-d) are the major products, as previously reported.⁵ However the yields of the epoxides (3a-d) are invariant with concentration whilst those of the esters (4a-d) are always very low, and independent of concentration. Therefore it seems that in apolar solvents, heterolytic cleavage of the peroxides (1) occurs to only a limited extent and that the epoxides (3) are predominantly formed by a different route probably involving an intramolecular synchronous rearrangement, as shown in (A).



Both our previous results and those described above lead to the conclusion that the thermal conversion of aryl substituted *endo*-peroxides (1) takes different courses depending on temperature, solvent, and concentration. In a polar aprotic solvent, dipolar intermediates are formed which at low concentration rearrange to enol esters (4).⁶ At higher concentrations the intermolecular oxygen transfer between dipolar intermediates overcomes the intramolecular rearrangement leading mainly to the epoxides (3). In apolar solvents, especially at high temperatures, the main products are the furans (2).⁵ At lower temperatures loss of molecular oxygen competes with epoxide (3) formation, a process which may be interpreted as occurring by an intramolecular synchronous rearrangement.

Experimental

M.p.s are uncorrected. I.r. spectra were measured with chloroform as solvent on a Perkin-Elmer 399 spectrophotometer. ¹H N.m.r. spectra were recorded with deuteriochloroform as solvent, unless otherwise stated, on a Perkin-Elmer R 12 A or Bruker WH 270 spectrometer with tetramethylsilane as internal standard. The nitromethane and the carbon tetrachloride used in the oxidation reactions and in the thermal conversions were anhydrous. Silica gel [0.05–0.20 mm (Merck)] and light petroleum (b.p. 30–50 °C) were used for column chromatography.

General Procedure for the Preparation and the Thermal Conversion of the 2,5-Epidioxy-2,5-dihydro-2,5-diphenylfurans (1a–d) in Nitromethane.—Two solutions (15×10^{-2} M) of the

† The *endo*-peroxides (1a–d) are hardly soluble in apolar light petroleum, thus carbon tetrachloride was used. The solutions at high concentration were made consistently with this solvent.

Table 1. Thermal conversion of the *endo*-peroxides (1a—d) at 4 °C

Substrate	Solvent ^a	Concentration (M × 10 ⁻²)	Yields (%) ^b				Polymeric material ^c
			(2)	(3)	(4)	(5)	
(1a)	NM	15	—	63	30	Trace	3
	NM	2	—	6	84	Trace	7
	CT	15	Trace	43	10	22	23
	CT	2	—	46	12	15	24
(1b)	NM	15	10	62	19 ^d	3	5
	NM	2	7	2	77	10	3
	CT	10	54	20	8 ^d	7	7
	CT	2	57	20	7 ^d	5	5
(1c)	NM	15	6	61	16 ^d	3	6
	NM	2	4	3	77	7	7
	CT ^e	15	42	22	7 ^d	6	13
	CT ^e	2	45	22	7 ^d	10	9
(1d)	NM	15	2	78	11	2	2
	NM	2	2	11	69	4	5
	CT	2	10	72	2	8	3
	CT	0.4	18	70	3	3	2

^a NM = nitromethane and CT = carbon tetrachloride. ^b Deduced on the basis of the ¹H n.m.r. spectrum and confirmed by silica gel chromatography. ^c Calculated on the basis of the molecular weight of the starting furan + O₂/2. ^d Percentage yields include the isomer alkyl 2-benzoyl-3-benzoyloxypropenoate. ^e Percentage yields previously reported⁵ were little different; however in the present case the peroxide (1c) was directly prepared in carbon tetrachloride.

Table 2. Physical, spectral, and analytical data of the epoxides (3a,b,d)

Product	M.p. (°C)	ν _{max.} (CHCl ₃)/cm ⁻¹	δ _H (CDCl ₃) (J/Hz)	Formula	Analysis (%)	
					Found	Required
(3a)	Oil	1 682	1.83 (3 H, s, Me), 4.31 (1 H, s, CH), 7.25—8.20 (10 H, m, Ar)	C ₁₇ H ₁₄ O ₃	76.05 (76.67)	5.5 (5.30)
(3b)	Oil	1 748, 1 685	3.81 (3 H, s, OMe), 4.83 (1 H, s, CH), 7.35—8.20 (10 H, m, Ar)	C ₁₈ H ₁₄ O ₃	69.25 (69.67)	4.6 (4.55)
(3d)	108—109 ^a	1 720, 1 689	2.35 (3 H, s, Me), 4.62 (1 H, s, CH), 7.30—8.10 (10 H, m, Ar)	C ₁₈ H ₁₄ O ₄	73.35 (73.46)	4.9 (4.80)

^a Recrystallization solvent, light petroleum (b.p. 40—70 °C).

diphenylfurans (2a—d) (1 mmol) in nitromethane were irradiated with a halogen-superphot lamp (Osram, 650 W) in the presence of Methylene Blue (8 × 10⁻³ mmol). During the irradiation, dry oxygen was bubbled through the solutions which were kept at -15 °C [furan (1a) solution was kept at -20 °C]. After completion of singlet oxidation, when the ¹H n.m.r. spectrum of the reaction mixture showed only the presence of the *endo*-peroxides (1a—d),^{5,6} one of the solutions was warmed to 4 °C and kept at this temperature. The other solution was diluted to 2 × 10⁻²M with nitromethane pre-cooled to 4 °C and kept at this temperature. The solutions were periodically sampled and the samples analyzed by ¹H n.m.r. spectroscopy. When the inspection of the ¹H n.m.r. spectrum of every solution showed that the peroxide (1) was entirely converted into compounds (2), (3), (4), and (5), the solvent was removed under reduced pressure and the residue was chromatographed on silica gel (15 g). Elution with light petroleum—diethyl ether (19:1 and 4:1 v/v)* and diethyl ether gave successively, the furans (2a—d), the enol esters (4a—d), the ethylenes (5a—d), the epoxides (3a—d), and polymeric material. The results are shown in Table 1. The

hitherto known compounds were identified by comparison (i.r. and ¹H n.m.r.) with those of authentic samples.^{1,5,6} The physical, spectral, and analytical data of the epoxides (3a,b,d) are listed in Table 2. It is to be noted that epoxide (3a) polymerizes with time.

General Procedure for the Preparation and the Thermal Conversion of the 2,5-Epidioxy-2,5-dihydro-2,5-diphenylfurans (1a—d) in Carbon Tetrachloride.—Two solutions of the diphenylfurans (2a—d) (1 mmol) were dissolved or suspended [(2a) is hardly soluble] in carbon tetrachloride. The quantities of solvent used were consistent with the solubility of the peroxides (1a—d) (see Table 1). Oxidation was carried out in the presence of tetraphenylporphyrin (3.6 × 10⁻⁴ mmol) with the procedure described above. One of the solutions of the peroxides (1a—d) was warmed at 4 °C and kept at this temperature. The other was diluted to the concentration reported

* For the mixture obtained by thermal conversion of the peroxide (1d), light petroleum—diethyl ether (19:1, 4:1, and 1:1 v/v) was used as eluant.

in Table 1 with carbon tetrachloride pre-cooled to 4 °C, and kept at this temperature. Thermal conversion control and isolation of the products were carried out as described above. The results are shown in Table 1.

Thermal Conversion of the Ethyl 2,5-Epidioxy-2,5-dihydro-2,5-diphenylfuran-3-carboxylate (1c) in the Presence of cis-3-Benzoyl-1-phenylpent-2-ene-1,4-dione (5d).—To a solution of the peroxide (1c)⁵ (1 mmol) in nitromethane (5.6 ml) kept at -15 °C was added a solution, pre-cooled to -15 °C, of the ethylene (5d)¹ (1 mmol) in nitromethane (1 ml). The solution was stirred while being allowed to warm to 4 °C and kept at this temperature. After 50 h inspection of the ¹H n.m.r. spectrum of the solution showed only signals for the ethylene (5d) and products deriving from the thermal conversion of the peroxide (1c). The solvent was removed under reduced pressure and the mixture was chromatographed on silica gel (30 g). Elution with light petroleum–diethyl ether (19 : 1 and 4 : 1 v/v) and diethyl ether gave successively the furan (2c) (11 mg, 4%), the ester (4c) (39 mg, 1.2%), the ethylene (5c) (21 mg, 7%), the epoxide (3c) (198 mg, 61%), the ethylene (5d) (269 mg, 0.97 mmol), and polymeric material (27 mg, 9%).

Thermal Conversion of the Ethyl 2,5-Epidioxy-2,5-dihydro-2,5-diphenylfuran-3-carboxylate (1c) in the Presence of cis-2-Methyl-1,4-diphenylbut-2-ene-1,4-dione (5a).—A nitromethane solution of the peroxide (1c)⁵ and of the ethylene (5a)¹² was prepared as described above for the compounds (1c) and (5d) and kept at 4 °C. After 50 h, inspection of the ¹H n.m.r. spectrum of the solution showed, in addition to the signals of the products deriving from the thermal conversion of the peroxide (1c), only the signals of the ethylene (5a). The solvent was removed under reduced pressure and the mixture was chromatographed on silica gel (30 g). Elution with light petroleum–diethyl ether (19 : 1 and 4 : 1 v/v) and diethyl ether gave successively the furan (2c) (14 mg, 5%), the ester (4c) (55 mg, 17%), the ethylene (5c) (12 mg, 4%), the ethylene (5a) (245 mg, 0.98 mmol), the epoxide (3c) (200 mg, 62%), and polymeric material (30 mg, 10%).

Thermal Conversion of the 2,5-Epidioxy-2,5-dihydro-3-methyl-2,5-diphenylfuran (1a) in the Presence of the endo-Peroxide (1c).—To a solution of the peroxide (1a)⁶ (1 mmol) in nitromethane (6 ml) kept at -20 °C was added a solution, pre-cooled to -20 °C, of the peroxide (1c)⁵ (1 mmol) in nitromethane (6 ml). The solution was stirred while being allowed to warm to 4 °C and kept at this temperature. After 30 min, inspection of the ¹H n.m.r. spectrum of the solution showed, in addition to the signals of the products deriving from the thermal conversion of the peroxide (1a), only the signals of the peroxide (1c). Diethyl sulphide (2 mmol), pre-cooled to 4 °C, was added to the solution which was then kept at 4 °C. After 12 h the solvent and unchanged diethyl sulphide were removed under reduced pressure and the mixture chromatographed on silica gel (30 g). Elution with light petroleum–diethyl ether (4 : 1, v/v) and diethyl ether gave successively the ester (4a) (191 mg, 72%), the ethylene (5a)

(5 mg, 2%), the ethylene (5c) (292 mg, 95%), the epoxide (3a) (40 mg, 15%), and polymeric material (12 mg, 5%).

Control experiments showed that the epoxide (3c) was quantitatively recovered after addition of diethyl sulphide and silica gel chromatography.

Reduction of Dimethyl 2,5-Epidioxy-2,5-dihydro-2,5-dimethylfuran-3,4-dicarboxylate by Diphenyl Sulphide.—To a solution of dimethyl 2,5-epidioxy-2,5-dihydro-2,5-dimethylfuran-3,4-dicarboxylate^{4,5} (1 mmol) in carbon tetrachloride (6 ml) was added diphenyl sulphide (2 mmol) and the solution was warmed to 77 °C. After 60 min the ¹H n.m.r. spectrum of the reaction mixture showed the presence of the dimethyl 2,3,4,5-diepoxy-2,3,4,5-tetrahydro-2,5-dimethylfuran-3,4-dicarboxylate^{4,5,*} and of the dimethyl 2,5-dioxohexene-3,4-dicarboxylate^{1,†} in ca. 10:1 molar ratio (on the basis of the relative areas of the methyl singlets). When the reaction was carried out at room temperature the reaction was very slow; however after 3 days the ¹H n.m.r. spectrum of the reaction mixture showed the signals of the hexendione, in addition to the signals of the endo-peroxide, of the diepoxy, and of polymeric material.

Control experiments showed that diepoxy remains unchanged by addition of diphenyl sulphide at 77 °C.

Acknowledgements

This work has been financially supported by Progetto Finalizzato del C.N.R. Chimica Fine e Secondaria. We thank Miss M. Marmorino for technical assistance.

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* $\delta_{\text{H}}(\text{CCl}_4)$ 1.71 (s, 6 H, 2 × Me) and 3.83 (s, 6 H, 2 × OMe).

† $\delta_{\text{H}}(\text{CCl}_4)$ 2.23 (s, 6 H, 2 × Me) and 3.89 (s, 6 H, 2 × OMe).