THE PHOTO-OXYGENATION OF DIHYDROPYRANS. FORMATION OF 1,2-DIOXETANES AND 1,2,4-TRIOXANES

Charles W. Jefford*, Marcelo Ferrufino Deheza, and Jian Bo Wang

Department of Organic Chemistry, University of Geneva
1211 Geneva 4, Switzerland

Abstract- 3,4-Dihydro-2*H*-pyran (**1**), 5,6,7,8-tetrahydrochroman (**9**), and 2-oxabicyclo[4.6.0]dodec-1(6)-ene (**13**) on dye-sensitized photo-oxygenation give the corresponding 1,2-dioxetanes (**3**), (**10**), and (**14**) in yields of 35-53% as isolable, stable entities with the exception of **10**. 2-Hydroperoxy-5,6-dihydro-2*H*-pyran (**5**) is also obtained from **1** in 15% yield. No hydroperoxide is formed from **9**, whereas **13** affords 3,4,6,7,8,9-hexahydro-2*H*-cycloocta[*b*]pyran-4a-yl hydroperoxide (**15**) in variable, but minor yields depending on the choice of solvent, temperature and sensitizer. Further [2 + 2] addition to **15** produces the 1,2-dioxetane (**16**). Repetition of the photo-oxygenation of **1**, **9** and **13** in the presence of acetaldehyde affords the same products as before. In the case of **1**, the *cis*-fused epimeric 1,2,4-trioxanes (**7**) are additionally formed in 2% yield. TMSOTf-catalyzed treatment of **3**, **10**, and **14** with acetaldehyde affords the corresponding 1,2,4-trioxanes in yields of 30, 30 and 43%. Thermolysis of **3**, **10**, and **14** breaks the dioxetane ring to produce the monocyclic keto lactones.

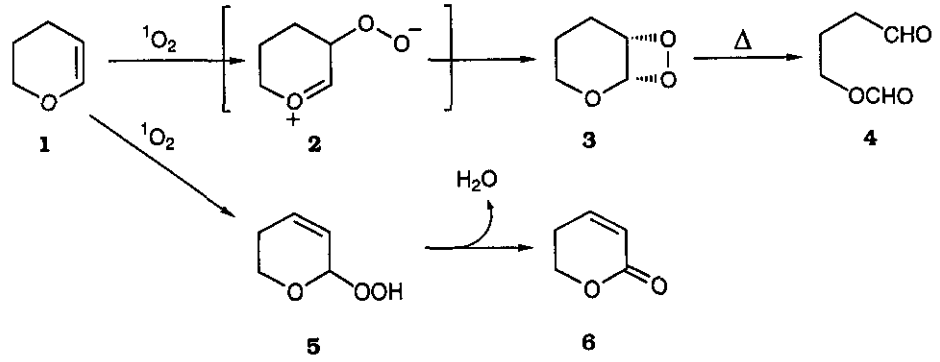
INTRODUCTION

A long-standing question concerns the nature of the primary intermediates that are formed by the reaction of singlet oxygen with olefins.[1] Depending on the conditions used, a mono-olefin can produce a hydroperoxide, a 1,2-dioxetane or both. 3,4-Dihydro-2*H*-pyran (**1**) is typical (Scheme 1). The dye-sensitized photo-oxygenation of **1** in polar solvents leads predominantly to the formyloxybutanal (**4**), whereas in non-polar solvents, the hydroperoxide (**5**) prevails, but decomposes to the α,ß-unsaturated ketone (**6**).[2] The relative importance of these two reaction courses has been ascribed to the role of solvent[3] in stabilizing the zwitterionic peroxide intermediate (**2**),[4] since hydroperoxidation (**1** → **5**) is essentially concerted and therefore far less subject to environmental influences. Calculations have lent credence to the gross structure depicted by **2**.[5,6] Normally, the zwitterionic peroxide (**2**) subsequently evolves to the 1,2-dioxetane (**3**) which then breaks apart giving **4**.

Dedicated to the memory of the late Professor Shun-ichi Yamada.

Despite further studies with **1** and its derivatives,[3,7] only circumstantial evidence has been obtained for **2** and the dioxetane (**3**) owing to the supposed inherent instability of the latter which precludes its isolation under the experimental conditions. We have previously demonstrated that intermediates such as **2** can be characterized by trapping them with protic solvents and electrophiles such as aldehydes.[8] We now describe the photo-oxygenation of **1** and two related bicyclic derivatives, 5,6,7,8-tetrahydrochroman (**9**) and 2-oxabicyclo[4.6.0]dodec-1(6)-ene (**13**), alone, and in the presence of acetaldehyde as a potential trapping agent.

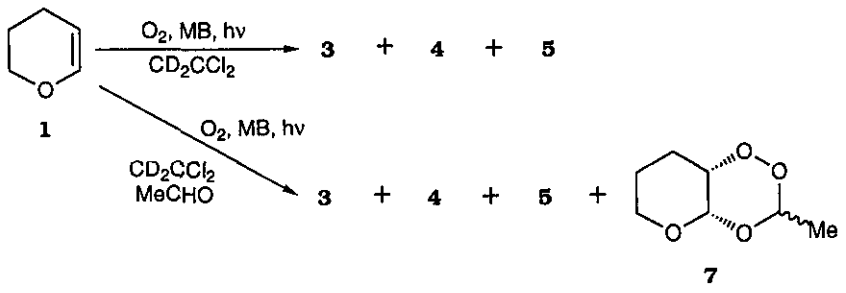
Scheme 1



RESULTS

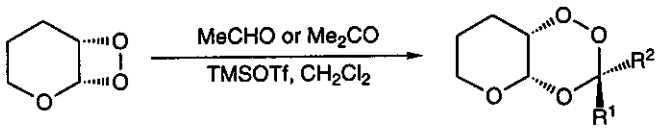
The methylene blue (MB)-sensitized photo-oxygenation of 3,4-dihydro-2*H*-pyran (**1**) in CD_2Cl_2 for 20 min at −78 °C occurred to the extent of 40% to give the 1,2-dioxetane (**3**), its cleavage product (**4**) and the hydroperoxide (**5**) in a ratio of 80:5:15 (Scheme 2). The photo-oxygenation was repeated at −78 °C for 2 h. Submission of the crude reaction mixture to flash chromatography over silica at −30 °C furnished pure **3** in 35% yield. Contrary to expectation, **3** was a stable, colorless oil which decomposed only slowly between 0 and 4 °C. Repetition of the photo-oxygenation under the same conditions, but in the presence of an excess of acetaldehyde, gave **3**, **4**, and **5** in the same ratio and yield together with a small amount (2%) of the *cis*-fused 1,2,4-trioxane (**7**) as a mixture of epimers.

Scheme 2



The identity of **7** was corroborated by comparing it with an authentic sample prepared by condensing **3** with acetaldehyde in the presence of trimethylsilyl trifluoromethanesulfonate (TMSOTf) as catalyst (Scheme 3). The epimers (**7**) were formed in 30% yield. Similar condensation of **3** with acetone gave the corresponding *cis*-fused 3,3-dimethyl derivative (**8**) in 12% yield.

Scheme 3



3

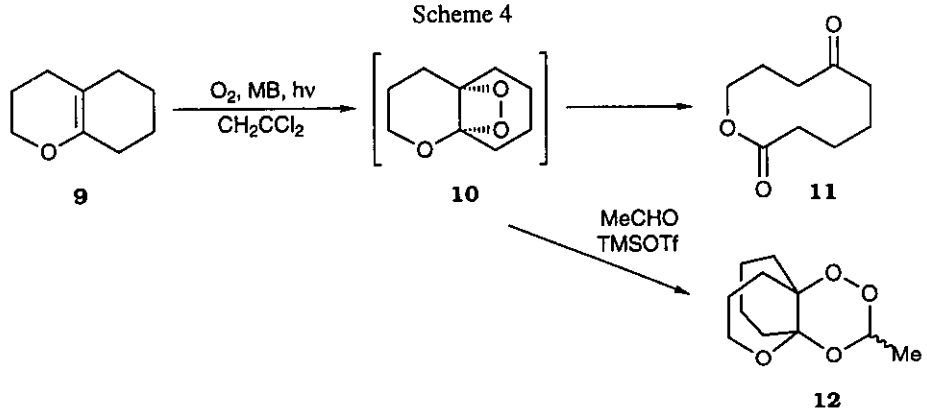
7a R^1 = H, R^2 = Me

7b R^1 = Me, R^2 = H

8 R^1 = R^2 = Me

The MB-sensitized photo-oxygenation of 5,6,7,8-tetrahydrochroman (**9**) in CH_2Cl_2 at −50 to−40 °C for 2 h produced solely 6-ketononalide (**11**) in 52% yield (Scheme 4). Thin layer chromatography of the crude reaction mixture revealed an unstable intermediate that turned white when exposed to iodine vapor thereby permitting its assignment as the 1,2-dioxetane (**10**). The starch-potassium iodide test was also positive. In a second experiment, the crude reaction mixture was treated with an excess of acetaldehyde and a catalytic amount of TMSOTf. The tricyclic 1,2,4-trioxane (**12**) was obtained as an epimeric mixture in 30% yield (Scheme 4).

Scheme 4

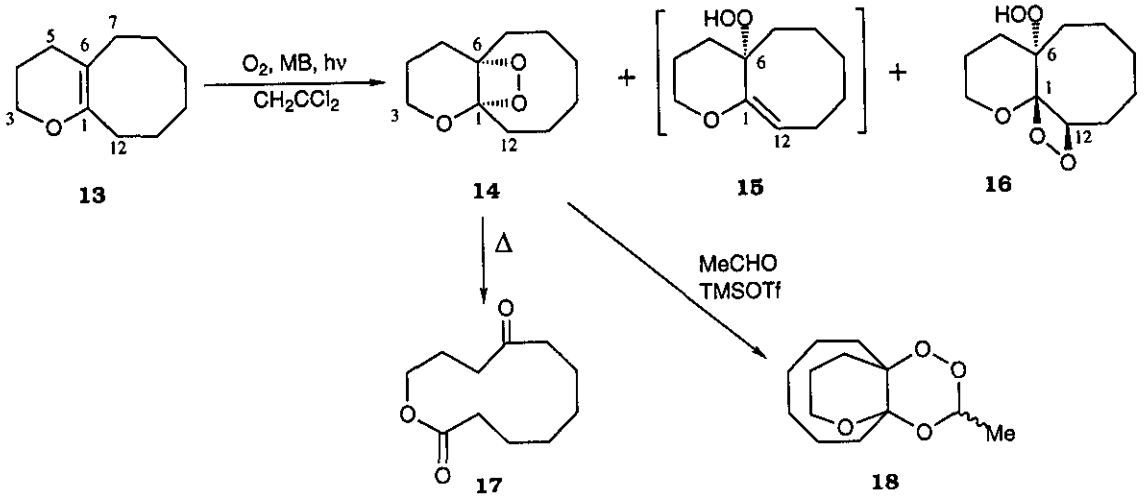


9 **10** **11** **12**

The MB-sensitized photo-oxygenation of 2-oxabicyclo[4.6.0]dodec-1(6)-ene (**13**) in CH_2Cl_2 at −25 °C for 50 min gave two products which were stable at rt (Scheme 5). Chromatography enabled the 1,2-dioxetane (**14**) and the hydroperoxy dioxetane (**16**) to be isolated in a ratio of 3.3:1. Repetition of the photo-oxygenation of **13** in CCl_4 at −23 °C, but on sensitization with *meso*-tetraphenylporphin (TPP) followed by removal of the solvent and chromatographic separation, furnished **14** and **16** in a ratio of 1:2.1. Analysis of the crude product mixture revealed the fugitive existence of the likely precursor to **16**, the hydroperoxide (**15**), which, despite all efforts, could not be isolated and properly characterized.

The net reversal in the ratio of **14** to **16** in the last experiment was noteworthy. Consequently, the effect of changing solvent and temperature on the course of photo-oxygenation was studied. The results (Table 1) did not show any significant effect of solvent polarity on the product distribution, but low temperatures favored the formation of the dioxetane (**14**). The nature of the sensitizer played a role as well. Rose bengal (RB) and methylene blue (MB) displayed a bias towards **14**, whereas changing the sensitizer to TPP favored **16** over **14**, except at low temperature.

Scheme 5



13 14 15 16 17 18

Table 1. Formation of 1,2-dioxetanes (**14**) and (**16**), and hydroperoxide (**15**) by the dye-sensitized photo-oxygenation of 2-oxabicyclo[4.6.0]dodec-1(6)-ene (**13**)

Solvent/sensitizer/temp.	**14** (%)[a]	**16** (%)[a]	**15** (%)[a]
MeOH/RB/−25 °C	79[b]	-	14
Me_2CO/MB/−25 °C	74	13	13
CH_2Cl_2/MB/−25 °C	76	24	-
CH_2Cl_2/MB/−78 °C	100	-	-
CH_2Cl_2/TPP/−25 °C	59	37	4
CH_2Cl_2/TPP/−78 °C	95	4	1
CCl_4/TPP/−23 °C	27	66	7

[a] Estimated from the NMR spectrum (200 MHz) of the crude product

[b] NMR reveals an additional unknown product (~7%)

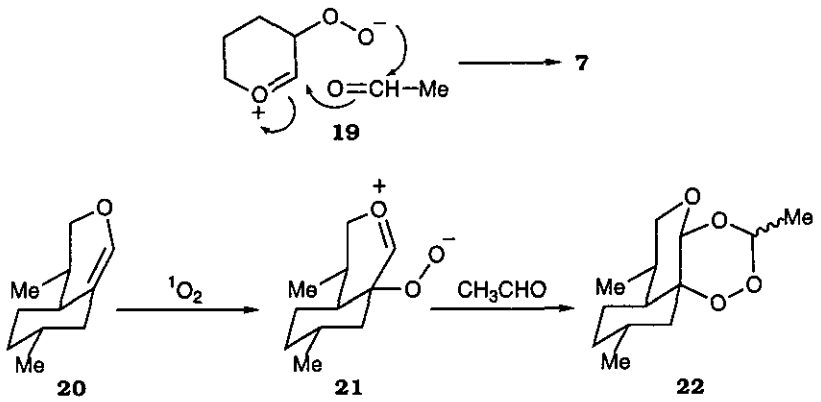
The tricyclic dioxetane (**14**) exhibited high thermal stability. However, on heating at 70 °C in CCl_4 decomposition was complete after 67 h. Purification afforded 7-ketoundecanolide (**17**) in 45% yield. Furthermore, treatment of **14** with acetaldehyde in CH_2Cl_2 in the presence of TMSOTf followed by chromatography gave the epimeric 1,2,4-trioxanes (**18**) in 43% yield (Scheme 6). Lastly, there was no evidence of 1,2,4-trioxane formation when **13** was photo-oxygenated in a solution of CH_2Cl_2 containing acetaldehyde in excess.

DISCUSSION

The results confirm expectation. The photo-oxygenation of the 3,4-dihydro-2*H*-pyran (**1**) undoubtedly proceeds through the zwitterionic peroxide (**2**) as attested by its reaction *in situ* with acetaldehyde. Annihilation of the charges by addition across the carbonyl function in the anticipated electronic sense through the arrangement (**19**) creates the 1,2,4-trioxane ring (**7**) (Scheme 6). However, unlike the

analogous intermediate (**21**) derived from the bicyclic dihydropyran (**20**) which gives sizable amounts of trioxane (**22**) in the presence of acetaldehyde,[9] **2** mainly eludes capture by closing to the dioxetane (**3**). The inefficiency of the trapping of **2** is also reflected in the low yield of **7** obtained by the TMSOTf-catalyzed reaction of **3** with acetaldehyde.

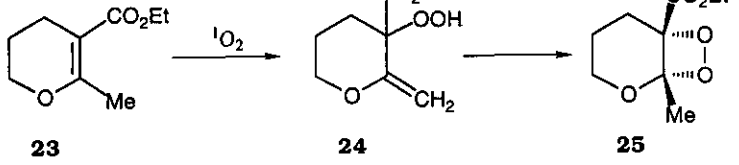
Scheme 6



Once formed, **3** enjoys considerable thermal stability presumably owing to its ability to adopt a twist conformation. Previously, it was not possible to isolate and characterize **3**.[2b] The present finding demonstrates that the intrinsic puckering of a dioxetane fused to a six-membered ring does not automatically confer instability.[10-12] Obviously, heating is deleterious causing the dioxetane ring to break apart to the dicarbonyl product (**4**).

The 1,2-dioxetane (**3**) is the first instance of an isolated and characterized [2 + 2] adduct from a monocyclic dihydropyran. The only other example of a related dioxetane is **25**, which has been reported[7] to arise by isomerization of the allylic hydroperoxide (**24**), the primary product of the photo-oxygenation of 5-ethoxycarbonyl-6-methyl-3,4-dihydro-2*H*-pyran (**23**) (Scheme 7).

Scheme 7

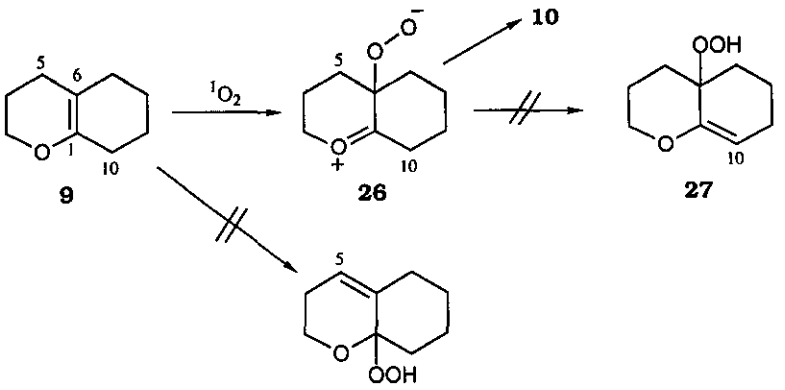


The hydroperoxide (**5**) that is formed at the same time as **3** is also stable under the reaction conditions and resists dehydration. Thus the ene-reaction is not perturbed by acetaldehyde and clearly follows an independent course. It should be noted that the ratio of cyclo-addition to hydroperoxidation in the present instance is 5.66. Earlier,[2b] the ratio in the same solvent, CH_2Cl_2, was determined as 2.67, but the difference may be due to changing the sensitizer from MB to TPP.[13]

In contrast, 5,6,7,8-tetrahydrochroman (**9**) undergoes no ene-reaction at all with singlet oxygen and follows instead the cyclic addition route. The zwitterionic peroxide (**26**), the presumed first-formed

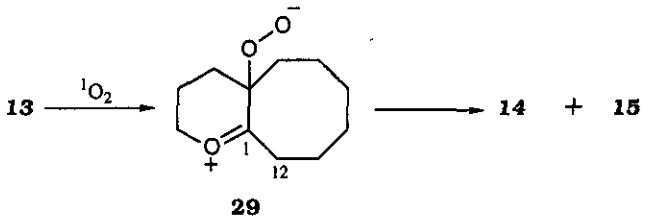
intermediate, is even more elusive than **2**, because not a trace of trioxane could be detected when acetaldehyde was present (Scheme 8). The zwitterion must close exceedingly rapidly to the 1,2-dioxetane (**10**), which proves to be highly unstable, because scission to the cyclic lactone (**11**) occurs spontaneously. These results indicate that attack of singlet oxygen on the double bond of **9** does not engender a transition state leading to hydroperoxidation. The apparently available H-atoms at the C5 and C10 positions are probably out of reach for conformational reasons. Neither hydroperoxide (**27**) nor (**28**) was detected (Scheme 8). Similar behavior has been reported for the lower homologue of **9**; only dioxetane formation was observed.[14] For the same reasons, the 1,2-dioxetane (**10**) is pre-disposed for easy cleavage. In fact, the analogue of **10** lacking the pyran O-atom exhibits similar instability.[11]

Scheme 8



Increasing the size of the second ring provides greater flexibility and provides more avenues for reaction. Singlet oxygen attacks the C6 terminus of the double bond of 2-oxabicyclo[4.6.0]dodec-1(6)-ene (**13**) giving the presumed intermediate peroxide (**29**) (Scheme 9). Again **29** must be very short-lived because it could not be trapped as trioxane. It behaved just like **26**, cyclizing instantaneously to the dioxetane (**14**).

Scheme 9

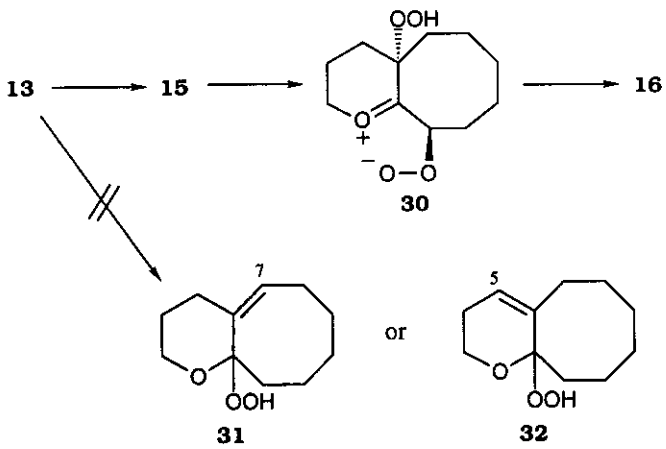


At the same time the conformational freedom of the eight-membered ring enables the distal peroxide atom to abstract one of the hydrogen atoms at the C12 position so forming the allylic hydroperoxide (**15**). Although direct evidence for **15** was not available, it can be supposed that as an electron-rich olefin **15** would react instantly with a second molecule of singlet oxygen. Attack presumably occurs on the face of the double bond that is *trans* to the hydroperoxy substituent (Scheme 10).

The resulting zwitterionic peroxide (**30**) can only exercise one option for reaction, since allylic H-atoms are unavailable, namely, closure to the 1,2-dioxetane (**16**). Other possibilities, in particular formation of the allylic peroxides (**31**) and (**32**), are less likely, especially in view of the inertness of **9** to hydroperoxidation where a O-atom-directed *cis*-effect might have operated.[15] The production of **32** is even more improbable, since it would run counter to the *cis*-effect. Finally, [2 + 2] addition of singlet oxygen to unactivated olefins like **31** and **32** finds little precedent.[16]

The effect of different reaction conditions is in keeping with the course of double oxygenation (Table). Higher temperature, less polar solvent, and TPP rather than MB, all favor the formation of **15** and its oxygenated adduct (**16**).

Scheme 10



CONCLUSIONS

The present findings demonstrate that zwitterionic peroxides are implicated as intermediates in the dye-sensitized photo-oxygenation of electron-rich substrates of the 3,4-dihydro-2*H*-pyran type. The isolation of the 1,2-dioxetanes (**3**) and (**14**) obtained by [2 + 2] addition of singlet oxygen to the parent (**1**) and its bicyclic derivative (**13**) reveals that they are more stable than originally supposed. The attendant course of hydroperoxidation is shown to depend crucially on conformation which determines the availability of hydrogen atoms at future allylic positions. The dioxetane (**16**) obtained from the allylic hydroperoxide (**15**) is also stable. The thermal decomposition of dioxetanes such as **10** and **14** has preparative value by providing access to cyclic lactones (**11**) and (**17**).

Unlike 1,2-dioxetanes obtained from acyclic enol ethers[17] and substituted indoles[18], it appears that pyran-dioxetanes, e.g. (**3**), (**10**), and (**14**), are of only average utility for synthesis, combining less effectively with acetaldehyde to give the corresponding trioxanes (**7**), (**12**), and (**18**). However, **12** and **18** are worth noting as the first representatives of trioxanes displaying a 'propeller' structure.

ACKNOWLEDGMENTS

We are indebted to the UNDP/World Bank/WHO Special Programme for Research and Training in Tropical Diseases for providing a stipend (M.F.D.). We thank Dr. T. Hatsui, Kyushu University, Fukuoka, Japan, for fruitful discussions. Thanks are also due to Messieurs A. Pinto and J.P. Saulnier for the NMR measurements, and Professors A. Buchs and F. Gülaçar for obtaining the MS data.

EXPERIMENTAL PART

1. General. All solvents were either puriss grade (Fluka or Aldrich) or distilled prior to use. TLC: silica gel F254 (Merck, layer thickness 0.20 mm). Column chromatography: Merck silica gel 60 (230-400 mesh). IR: Perkin-Elmer-681 spectrophotometer. Mps were determined on a Reichert hot stage microscope and are uncorrected. ^{1}H- and ^{13}C-NMR: Bruker-AMX-400, Bruker-WH-360, Varian-XL-200 spectrometers; chemical shifts (δ) in ppm relative to internal TMS (= 0 ppm), coupling constants (*J*) in Hz; commercial $CDCl_3$ was used without further purification; ^{13}C-NMR spectra are recorded using APT[19] or DPT[20] and are assigned as o (odd) for C-atoms attached to 1 or 3 H-atoms and e (even) for C-atoms without or with 2 attached H-atoms. MS: *m/z* (intensities in % rel. to base peak); Finnigan GC/MS-4023 instrument using the INCOS data system; electron impact, 70 eV. Elemental analyses were carried out by Dr. H.J. Eder, Service de Microchimie, Institut de Chimie Pharmaceutique, Université de Genève.

2. Starting materials. 3,4-Dihydro-2*H*-pyran (**1**) was purchased from Fluka, Buchs, CH-9470, and used as such. 5,6,7,8-Tetrahydrochroman (**9**) was obtained[21] as a colorless liquid, bp 110 °C / 16 Torr.

2-Oxabicyclo[4.6.0]dodec-1(6)-ene (**13**) was prepared in four steps from cyclooctanone.[21] bp 96-98 °C / 8 Torr. IR (Neat): 2940, 1690, 1374, 1262, 1173, 1142, 1100, 1070, 936 cm^{-1} . ^{1}H-NMR (200 MHz): δ 3.82-3.89 (m, OCH_2). ^{13}C-NMR (50 MHz): δ 23.40 (e), 24.43 (e), 26,42 (e), 26.64 (e), 28,96 (e), 29.05 (e), 29.84 (e), 30.80 (e), 65.70 (e), 105.59 (e), 148.99 (e). Anal. Calcd for $C_{11}H_{18}O$: C 79.51, H 10.84. Found: C 79.26, H 10.98.

3.1 Photo-oxygenation of 3,4-dihydro-2*H*-pyran (**1**). A stream of oxygen was passed through a solution of **1** (38 mg, 0.45 mmol) and methylene blue (MB, 1.3 mg) in CD_2Cl_2 (1 mL) in an NMR tube screened by a filter (Jena KV 418) and irradiated with a tungsten filament lamp (Sylvania FFX, 500 W) at –78 °C for 30 min. At this point only 40% of the starting material had reacted. The NMR spectrum of the resulting mixture revealed the presence of the 1,2-dioxetane (**3**), 4-formyloxybutanal (**4**), and 2-hydroperoxy-5,6-dihydro-2*H*-pyran (**5**) in a ratio of 80:5:15. The NMR spectra of **4** and **5** were identical to those reported.[2]

3.2 The above photo-oxygenation was repeated with **1** (120 mg, 1.4 mmol) in CH_2Cl_2 (8 mL) containing MB (6 mg) at −78 °C for 2 h. The resulting solution was subjected to flash chromatography at −30 °C (silica gel, CH_2Cl_2, eluent). The 1,2-dioxetane (**3**) was isolated as a colorless oil (58 mg, 35%).

^{1}H-NMR of **3**: δ 1.84 (m, 2H), 1.90 (m, 1H), 2.30 (m, 1H), 3.95 (m, 1H), 4.50 (m, 1H), 5.50 (m, 1H), 6.12 (d, J = 6 Hz, 1H).

3.3 The photo-oxygenation of **1** was repeated in the presence of acetaldehyde (10 equiv.) according to paragraph 3.1. The products (**3**), (**4**), and (**5**) were obtained as before, but accompanied by trioxane (**7**) (2%) which was identified by comparison of its NMR spectrum with that of an authentic sample (see paragraph 4.1).

4.1 *exo*- and *endo*-3-Methyl-*cis*-tetrahydropyrano[2,3*e*]-1,2,4-trioxin (**7a** and **7b**). A solution of **1** (120 mg, 1.4 mmol) in CH_2Cl_2 (10 mL) containing MB (7 mg) was photo-oxygenated for 2 h at −78 °C. Next,

acetaldehyde (0.8 g, 18 mmol) and trimethylsilyl trifluoromethanesulfonate (TMSOTf) (310 mg, 1.4 mmol) were successively added. The resulting mixture was stirred for 10 min. Water (10 mL) was then added. The CH_2Cl_2 layer was separated, partially evaporated and subjected to column chromatography (silica gel, CH_2Cl_2 eluent). A mixture of **7a** and **7b** in a ratio of 1.2:1 (estimated from the NMR spectrum) was obtained (68 mg, 30%). Further chromatography gave **7a** as a pure colorless oil. IR ($CDCl_3$): 1450, 1368, 1130, 1070, 1040, 910 cm^{-1}. ^{1}H-NMR: δ 1.25 (d, J = 5.4 Hz, 3H), 1.58 (m, 1H), 1.74 (m, 2H), 2.00 (m, 1H), 3.54 (m, 1H), 4.07 (m, 1H), 4.38 (td, J = 3, 1.2 Hz, 1H), 4.72 (d, J = 1.2 Hz, 1H), 5.87 (q, J = 5.4 Hz, 1H). ^{13}C-NMR ($CDCl_3$): δ 17.7 (o), 21.8 (e), 23.9 (e), 60.9 (e), 76.6 (o), 92.4 (o), 100.3 (o). Anal. Calcd for $C_7H_{12}O_4$: C 52.49, H 7.55. Found: C 52.72, H 7.89. Spectroscopic data for **7b** were deduced from those of the mixture (**7a**, **7b**). IR ($CDCl_3$): 1470, 1445, 1380, 1100, 1000, 910 cm^{-1} . ^{1}H-NMR ($CDCl_3$): δ 1.32 (d J = 5.4 Hz, 3H), 1.73 (m, 2H), 1.95 (m, 1H), 2.43 (m, 1H), 3.62 (m, 1H), 3.85 (m, 2H), 5.11 (d, J = 3.4 Hz, 1H), 5.43 (q, J = 5.4 Hz, 1H). ^{13}C-NMR ($CDCl_3$): δ 17.3 (o), 19.6 (e), 26.0 (e), 66.2 (e), 74.2 (o), 92.3 (o), 95.4 (o). Anal. Calcd for $C_7H_{12}O_4$: C 52.49, H 7.55. Found: C 52.45, H 7.48.

4.2 *cis*-Tetrahydro-3,3-dimethylpyrano[2,3*e*]-1,2,4-trioxin (**8**). The procedure in paragraph 4.1 was used, but acetaldehyde was replaced by acetone. Trioxane (**8**) was obtained as a yellow oil in 12% yield. IR ($CDCl_3$): 1465, 1430, 1370, 1265, 1210, 1170, 1140, 1110, 1090, 1020, 990 cm^{-1} . ^{1}H-NMR ($CDCl_3$): δ 1.48 (s, 3H), 1.56 (s, 3H), 1.80-1.90 (m, 3H), 2.25 (m, 1H), 3.50 (m, 1H), 3.90 (m, 1H), 4.06 (m, 1H), 5.05 (s, 1H).

5. A solution of 5,6,7,8-tetrahydrochroman (**9**) (200 mg, 1.45 mmol), in CH_2Cl_2 (10 mL) containing MB (5 mg) was irradiated at −50 to −40 °C for 2 h. TLC revealed that all of **9** had reacted. The solution was allowed to stand at rt for 3 days. Removal of the solvent gave a crude residue which was purified by chromatography (hexane/ethyl acetate 1:1) to yield 6-ketononanolide (**11**) (130 mg, 52%). When the reaction was repeated with TMSOTf as catalyst, decomposition was complete after several minutes to give **11** in 47% yield. mp 68-70 °C, lit.,[21] 68-69 °C; IR ($CHCl_3$) 1740, 1724 cm^{-1} . ^{1}H-NMR (200 MHz, $CDCl_3$): δ 1.65-1.82 (m, 4H), 2.03-2.18 (m, 2H), 2.26-2.48 (m, 6H), 4.22 (t, J = 5.4 Hz, 2H).

6. *exo*- and *endo*-4-Methyl-2,3,5,7-tetraoxa[4.4.4.0]tetradecane (**12**). A solution of **9** (194 mg, 1.4 mmol) and MB (7 mg) in CH_2Cl_2 (10 mL) was irradiated at −50 to −40 °C for 2 h. Subsequent addition of acetaldehyde (8 mg, 18 mmol) and TMSOTf (310 mg, 1.4 mmol) followed by stirring, washing (H_2O) and drying ($MgSO_4$) afforded a solution which was evaporated. The resulting oil was subjected to chromatography (silica gel, CH_2Cl_2, eluent). Trioxane (**12**) was obtained as a mixture of isomers, (**12a**) and (**12b**) (90 mg, 30% yield, in a ratio of 1.5 to 1. Further chromatography afforded **12a** as a colorless oil. IR (CCl_4): 1460, 1450, 1400, 1230, 1200, 1145, 1120, 1090, 1050, 1020, 990, 930 cm^{-1} . ^{1}H-NMR ($CDCl_3$): δ 1.30 (d, J = 5.4 Hz, 3H), 1.40-1.70 (m, 8H), 1.82 (m, 1H), 2.02 (m, 1H), 2.32 (m, 1H), 2.82 (td, J = 13.5, 5 Hz, 1H), 3.64 (ddt, J = 11, 5, 1.8 Hz, 1H), 4.02 (ddd, J = 12, 11, 2.8 Hz, 1H), 5.70 (q, J = 5.4 Hz, 1H). ^{13}C-NMR ($CDCl_3$): δ 17.8q, 20.7t, 22.3t, 23.7t, 28.1t, 30.4t, 31.5t, 60.8t, 78.9s, 96.4s, 97.7d. Anal. Calcd for $C_{11}H_{18}O_4$: C 61.66, H 8.47. Found: C 62.01, H 8.74. ^{1}H-

NMR ($CDCl_3$) of **12b**: δ 1.23 (d, *J* = 5.4 Hz, 3H), 1.40-2.10 (m, 1H), 2.60 (td, *J* = 13.5, 4.5 Hz, 1H), 3.71 (td, *J* = 12.2, 2.0 Hz, 1H), 5.94 (q, *J* = 5.4 Hz, 1H). ^{13}C-NMR ($CDCl_3$) of **12b** (deduced from that of the mixture of **12a** and **12b**): δ 17.6q, 20.5t, 22.2t, 23.1t, 28.9t, 31.2t, 32.4t, 63.7c, 78.0s, 94.8d, 95.5s. Anal. of **12a** and **12b**. Calcd for $C_{11}H_{18}O_4$: C 61.66, H 8.47. Found: C 61.47, H 8.35.

7. General procedure for photo-oxygenation of 2-oxabicyclo[4.6.0]dodec-1(6)-ene (**13**) under various conditions. A solution of **13** (50 mg, 0.30 mmol) in the solvent (5 mL), together with sensitizer (2 mg), was irradiated with a 500-W high-pressure Na lamp for 50 min while O_2 was continuously passed at −25 °C or −78 °C. After evaporation of the solvent, the crude product was checked by ^{1}H-NMR spectroscopy. The product distribution was estimated from the integrals of the C3-H (δ 4.31-4.37, m) of **14**, the C(12)-H (δ 5.87, br d) of **15**, and the C(12)-H (δ 5.01, dd, J = 2.8 and 13.0 Hz) of **16**.

7.1. A solution of **13** (200 mg, 1.45 mmol) in CH_2Cl_2 (10 mL) containing methylene blue (5.0 mg) was irradiated with a 500-W high-pressure Na lamp for 50 min while O_2 was continuously passed at −25 °C. On completion of the reaction, the solvent was evaporated and the residue was subjected to column chromatography (Florisil, hexane/acetic anhydride 3:1) to give two fractions. The mobile fraction (126 mg, 53%) was dioxetane (**14**): oil, IR (neat): 2920, 1402, 1253, 1197, 1105, 1032, 998, 957 cm^{-1} . ^{1}H-NMR (400 MHz): δ 1.90-2.03 (m, 1H), 2.37-2.70 (m, 3H), 3.90-3.96 (m, 1H), 4.31-4.37 (m, 1H). ^{13}C-NMR (100 MHz): δ 18.26 (e), 24.53 (e), 24.74 (e), 25.19 (e), 25.40 (e), 27.18 (e), 32.96 (e), 33.91 (e), 62.46 (e), 90.16 (e), 108.45 (e). MS 198 (0.71, M^+), 180 (18.47), 154 (2.95), 126 (5.97), 112 (14.89), 97 (27.83), 84 (100), 68 (47.73), 55 (50.30). Anal. Calcd for $C_{11}H_{18}O_3$: C 66.64, H 9.15. Found: C 66.60, H 9.07. The polar fraction (46 mg, 16%) was the dioxetane-hydroperoxide (**16**). mp: 79-81 °C (recrystallized from hexane/acetone). ^{1}H-NMR (400 MHz): δ 3.03-3.14 (m,1H), 3.85-3.89 (m, 1H), 4.01-4.08 (m, 1H), 5.01 (dd, J = 2.8 Hz and 13.0 Hz), 8.77 (s, 1H). ^{13}C-NMR (100 MHz): δ 19.54 (e), 22.42 (e), 23.77 (e), 25.52 (e), 26.46 (e), 27.52 (e), 28.60 (e), 34.86 (e), 61.87 (e), 84.22 (e), 93.19 (o), 111.44 (e). IR (Nujol): 3458, 2943, 1380, 1251, 1112, 1075, 1040, 921, 862 cm^{-1} . MS: 199 (0.17), 198 [1.05, $(M-O_2)^+$], 181 (6.59), 165 (3.63), 139 (10.74), 111 (5.91), 97 (17.56), 81 (28.88), 71 (32.32), 55 (100). Anal. Calcd for $C_{11}H_{18}O_5$: C 57.39, H 7.83. Found: C 57.22, H 7.93.

7.2 A solution of **13** (190 mg, 1.15 mmol) in CCl_4 (10 mL) containing *meso*-tetraphenylporphin (4 mg) was irradiated for 50 min at −23 °C while O_2 was passed. On completion of the reaction, the solvent was removed. Chromatography of the residue (hexane/acetic anhydride 3:1) gave **14** (65 mg, 29%) and **16** (158 mg, 60%). An attempt to isolate hydroperoxide (**15**) failed.

8. Thermal decomposition of dioxetane (**14**). A solution of **14** (60 mg, 0.32 mmol) in CCl_4 (5 mL) was heated at 70 °C under N_2 for 67 h. The progress of the decomposition was followed by TLC (silica gel). On completion of the reaction, the solvent was evaporated. Purification of the crude product by column chromatography (hexane/acetic anhydride 1:1) gave crystalline 7-ketoundecanolide (**17**) (27 mg, 45%). mp: 58-59 °C, (recrystallized from hexane), lit.,[21] 42-43 °C. IR (Nujol): 2943, 1725, 1370, 1259, 1168, 987 cm^{-1} . ^{1}H-NMR (200 MHz): δ 2.30-2.37 (m, 2H), 2.41-2.52 (m, 4H), 4.04 (t, J = 5.4 Hz, 2H).

^{13}C-NMR (50 MHz): δ 21.10 (e), 22.69 (e), 23.45 (e), 24.73 (e), 24.92 (e), 33.47 (e), 40.48 (e), 40.68 (e), 64.73 (e), 173.94 (e), 210.31 (e). MS: 198 (0.61, M^+), 180 (6.78), 126 (3.19), 112 (8.76), 97 (22.20), 84 (89.10), 68 (59.46), 55 (100).

9. Reaction of the dioxetane (**14**) with acetaldehyde in the presence of TMSOTf. To a solution of **14** (100 mg, 0.50 mmol) in CH_2Cl_2 (5 mL) was added acetaldehyde (0.5 mL). The resulting solution was cooled to −78 °C while TMSOTf (0.1 mL, 0.50 mmol) was added. Stirring was maintained at −78 °C under N_2 for 1 h. Next, Et_3N (0.05 mL) and CH_2Cl_2 (10 mL) was added. The solution was then washed (H_2O, and brine), and dried ($MgSO_4$). Evaporation of the solvent gave an oily residue which was purified by column chromatography over silica gel (hexane/acetic anhydride 3:1) to give two fractions. The mobile fraction was 1,2,4-trioxane (**18a**) or (**18b**) (15.4 mg, 12.6%). Oil, IR (Neat): 2950, 1401; 1348, 1226, 1141, 1100, 1046, 985, 960 cm^{-1} . ^{1}H-NMR (200 MHz): δ 1.30 (d, J = 5.3 Hz, 1H), 2.60-2.71 (m, 1H), 2.88 (dt, J = 13.3, 5.0 Hz, 1H), 3.67 (ddt, J = 10.0, 4.9, 2.0 Hz, 1H), 4.01 (ddd, J = 12.9, 10.5, 2.8 Hz, 1H), 5.57 (q, J = 5.3 Hz, 1H). ^{13}C-NMR(50 MHz): δ 18.03 (o), 19.89 (e), 22.28 (e), 23.69 (e), 25.63 (e), 26.90 (e), 30.45 (e), 32.35 (e), 33.27 (e), 60.69 (e), 80.63 (e), 97.63 (o), 98.46 (e). MS: 243 [0.75, $(M+1)^+$], 227 (0.52), 199 (12.28), 182 (5.88), 166 (13.36), 154 (9.88), 111 (13.95), 97 (26.06), 84 (49.31), 69 (62.45), 55 (100). Anal. Calcd for $C_{13}H_{22}O_4$: C 64.44, H 9.15. Found: C 64.64, H 9.23. The mobile fraction was the epimeric 1,2,4-trioxane (**18b**) or (**18a**) (36.0 mg, 30%). Oil, IR (Neat): 2950, 1397, 1222, 1136, 1091, 1042, 961, 882, 741 cm^{-1}. ^{1}H-NMR (200 MHz): δ 1.23 (d, J = 5.41 Hz, 3H), 3.65 (dt, J = 11.5, 2.5 Hz, 1H), 3.82-3.93 (m, 1H), 5.95 (q, J = 5.4 Hz, 1H). ^{13}C-NMR (50 MHz): δ 17.49 (o), 20.53 (e), 21.17 (e), 22.31 (e), 26.03 (e), 26.72 (e), 29.22 (e), 32.57 (e), 33.41 (e), 63.41 (e), 80.21 (e), 94.62 (o), 97.10 (e). MS: 242 (0.16, M^+), 202 (2.03), 167 (1.26), 155 (4.62), 125 (21.88), 105 (46.84), 98 (5.67), 77 (88.94), 70 (30.67), 55 (100).

REFERENCES

1. R.W. Denny and A. Nickon, *Org. React.*, 1973, **20**, 133; A.A. Frimer, *Chem. Rev.*, 1979, **79**, 359.
2. a) G.O. Schenck, *Angew. Chem.*, 1952, **64**, 12; b) P.D. Bartlett, G.D. Mendenhall and A.P. Schaap, *Ann. N.Y. Acad. Sci.*, 1970, **171**, 79; c) E.C. Blossey, D.C. Neckers, A.I. Thayer, and A.P. Schaap, *J. Am. Chem. Soc.*, 1973, **95**, 5820.
3. A.A. Frimer, P.D. Bartlett, A.F. Boschung, and J.G. Jewett, *J. Am. Chem. Soc.*, 1977, **99**, 7977.
4. C.W. Jefford, *Helv. Chim. Acta*, 1981, **64**, 2534.
5. M.J.S. Dewar and W. Thiel, *J. Am. Chem. Soc.*, 1975, **97**, 3978.
6. Y. Yoshioka, S. Yamada, T. Kawakami, M. Nishino, K. Yamaguchi, and I. Saito, *Bull. Chem. Soc. Jpn.*, 1996, **69**, 2683.
7. Y.Y. Chan, X.Y. Li, C. Zhu, X.H. Liu, Y.D. Zhang, and H.K. Leung, *J. Org. Chem.*, 1990, **55**, 5497; Y.Y. Chan, C. Zhu, and H.K. Leung, *J. Am. Chem.* Soc., 1985, **107**, 5274.

8. C.W. Jefford in '*Dioxygen Activation and Homogeneous Catalytic Oxidation*', ed. by L.I. Simándi, Elsevier Science Publishers B.V., Amsterdam, 1991, pp. 555-564; C.W. Jefford, *Chem. Soc. Rev.*, 1993, 59.
9. C.W. Jefford, Y. Wang, and G. Bernardinelli, *Helv. Chim. Acta*, 1988, **71**, 2042.
10. W. Adam, L.A. Arias, A. Zahn, K. Zinner, K. Peters, E.-M. Peters, and H.G. von Schnering, *Tetrahedron Lett.*, 1982, **23**, 3251.
11. P. Lechten, G. Reissenweber, and P. Grubmüller, *Tetrahedron Lett.*, 1977, **18**, 2881.
12. A.L. Baumstark and P.C. Vasquez, *J. Org. Chem.*, 1986, **51**, 5213.
13. J.D. Boyd and C.S. Foote, *J. Am. Chem. Soc.*, 1979, **101**, 6758.
14. R.K. Boeckman, Jr., K.J. Bruza, and G.R. Heinrich, *J. Am. Chem. Soc.*, 1978, **100**, 7101.
15. S. Inagaki, H. Fujimoto, and K. Fukui, *Chem. Lett.*, 1976, 749; G. Rousseau, P. Le Perchec, and J.M. Conia, *Tetrahedron*, 1978, **34**, 3483; L.B. Harding and W.A. Goddard III, *Tetrahedron Lett.*, 1978, 747; D. Lerdal and C.S. Foote, *Tetrahedron Lett.*, 1978, 3227.
16. A.P. Schaap and K.A. Zaklika in '*Singlet Oxygen*', ed. by H.H. Wasserman and R.W. Murray, Academic Press, New York, 1979, pp. 174-238; D.J. Bogan, R.S. Sheinson, and F.W. Williams, *J. Am. Chem. Soc.*, 1976, **98**, 1034.
17. C.W. Jefford, J. Boukouvalas, and S. Kohmoto, *J. Photochem.*, 1984, **25**, 537; C.W. Jefford, J. Boukouvalas, S. Kohmoto, and G. Bernardinelli, *Tetrahedron*, 1985, **41**, 2081.
18. C.W. Jefford, D. Jaggi, J. Boukouvalas, S. Kohmoto, and G. Bernardinelli, *Helv. Chim. Acta*, 1984, **67**, 1104.
19. S.L. Patt and J.N. Shoolery, *J. Magn. Reson.*, 1982, **46**, 535.
20. G.A. Morris, *Magn. Reson. Chem.*, 1986, **24**, 371.
21. I.J. Borowitz, G.J. Williams, L. Gross, and R. Rapp, *J. Org. Chem.*, 1968, **33**, 2013; I.J. Borowitz, G. Gonis, R. Kelsey, R. Rapp, and G.J. Williams, *J. Org. Chem.*, 1966, **31**, 3032.

Received, 6th March, 1997