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PHOTOINDUCED REACTIONS—XLIX

PHOTOSENSITIZED OXYGENATION OF *cis. cis*-1.5-CYCLOOCTADIENE AND *cis*-CYCLOOCTENE[1]

T. MATSUURA, A. HORINAKA, H. YOSHIDA and Y. BUTSUGAN
Department of Synthetic Chemistry, Faculty of Engineering,
Kyoto University, Kyoto, Japan

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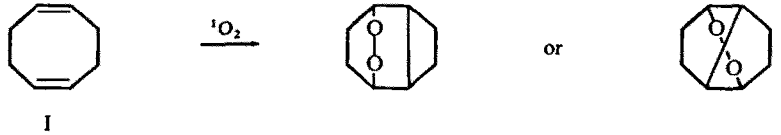
Abstract—Rose bengal-sensitized photooxygenation of *cis,cis*-1,5-cyclooctadiene (I) in methanol followed by reduction with sodium sulfite gave 2,5-cyclooctadienol (II) and 4-hydroxy-5-cyclooctenone (III). The latter product was found to result from an unusual transannular reaction of the initially formed hydroperoxide, 6-hydroperoxy-1,4-cyclooctadiene (VIII). Under similar conditions *cis*-cyclooctene (IX) gave 2-cyclooctenol (X). 1,5-Cyclooctadiene reacted seven times as fast as cyclooctene, probably due to the increase of electron density of the double bonds caused by their steric interaction.

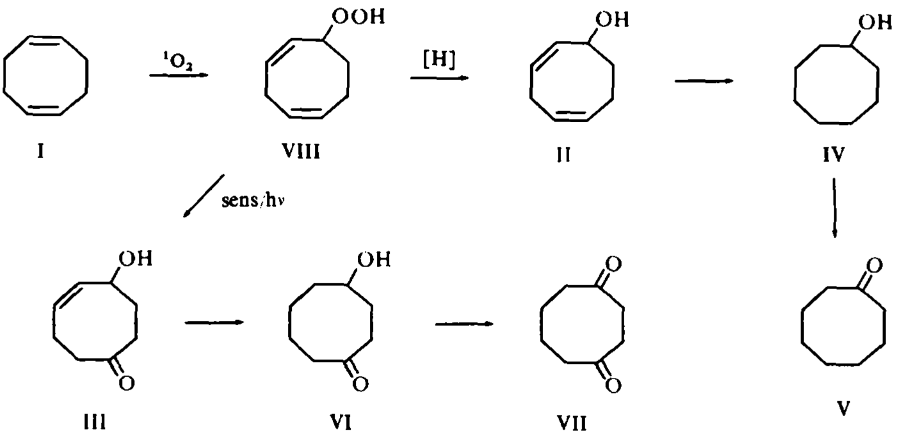
IN THE photosensitized oxygenation of olefins and dienes, the reactive species is known to be excited singlet oxygen, and three types of reactions are formulated: (i) simple olefins bearing an allylic hydrogen are converted to allyl hydroperoxides with migration of the double bond, (ii) singlet oxygen cycloadds to conjugated dienes like Diels-Alder reactions to give cyclic peroxides, and (iii) singlet oxygen cycloadds to electron-rich olefins to give 1,2-dioxetanes.[2]

On the other hand, it is well known that 1,5-cyclooctadiene (I), which has non-conjugated but sterically interacted double bonds, undergoes various types of transannular reactions: For instance, I reacts with benzoyl peroxide in chloroform to give 2-(trichloromethyl)-bicyclo[3.3.0] octane[3] and with sulfur dichloride to give 2,6-dichloro-9-thiabicyclo[3.3.1]nonane.[4] We investigated photosensitized oxygenation of I in hopes of a transannular addition of singlet oxygen to the diene system giving tricyclic peroxide or their further transformed products. Although this was not the case, it was found that in the resulting hydroperoxide an unusual transannular reaction had taken place.



I

When a methanol solution of 1,5-cyclooctadiene (I) was submitted to photosensitized oxygenation using rose bengal as sensitizer, one mole of oxygen was consumed. The reaction mixture was determined to be 54% mole of peroxide content. Reduction of the mixture with aqueous sodium sulfite gave 2,5-cyclooctadienol (II) and 4-hydroxy-5-cyclooctenone (III) in 16 and 12% yield respectively. When methylene blue was used as sensitizer, a similar result was obtained. The structure of these products was assigned from spectral data (Experimental) and confirmed by derivations to known compounds. The former product II was converted to cyclooctanone (V) *via* cyclooctanol (IV) and the latter III to 1,4-cyclooctanedione (VII) *via* 4-hydroxycyclooctanone (VI).



Although it is evident that II resulted from reduction of hydroperoxide VIII which is the well known primary product in the photosensitized oxygenation of simple olefins,[2] the result cannot distinguish whether III is formed directly from I by the attack of singlet oxygen or *via* hydroperoxide VIII. In order to clarify this, the photooxygenation reaction of I was followed as a function of time. At various reaction times, an aliquot was analyzed by VPC after reduction of the aliquot with triphenylphosphine. The ratio of II to III was found to decrease with reaction time (Fig 1). The result suggests that hydroperoxide VIII may be a precursor of III.

In order to confirm this, the mixture obtained after the absorption of one mole of oxygen was treated under nitrogen in three ways: (i) successive irradiation, (ii) refluxing in the dark, and (iii) standing at room temperature in the dark. The amounts of II and III relative to an added standard substance (diphenylmethane) were determined by VPC. The results shown in Fig 2 clearly indicated that 4-hydroxy-5-cyclooctenone (III) was formed from hydroperoxide VIII during irradiation in the presence of sensitizer.

The participation of singlet oxygen in the present reaction was ascertained by the reaction of I with chemically generated singlet oxygen.[5] Treatment of I with hydrogen peroxide and sodium hypochlorite in aqueous methanol followed by reduction with sodium sulfite yielded II but no 4-hydroxy-5-cyclooctenone (III). This again confirmed that III is formed from hydroperoxide VIII by irradiation in the presence of sensitizer. Irradiation of cyclooctene (IX) and t-butylhydroperoxide in the presence of rose bengal under nitrogen yielded only a minute amount of 2-cyclooctenol after reduction of the reaction mixture. The detailed mechanism for the formation of III from VIII remains to be elucidated. However, it should be noted that inspection of a

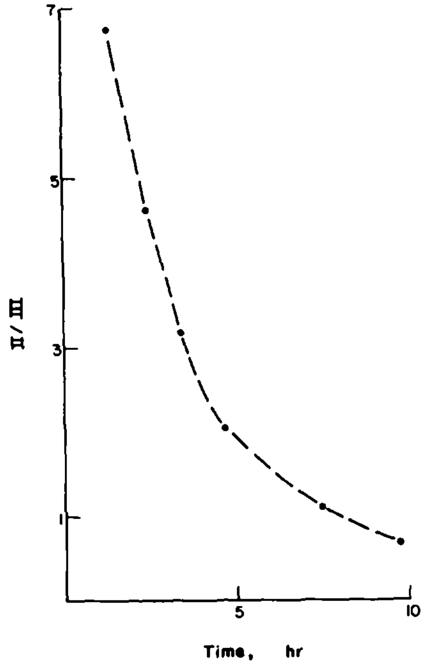


Fig 1. Time dependence of the product ratio (II/III) in the photosensitized oxygenation of 1,5-cyclooctadiene (I)

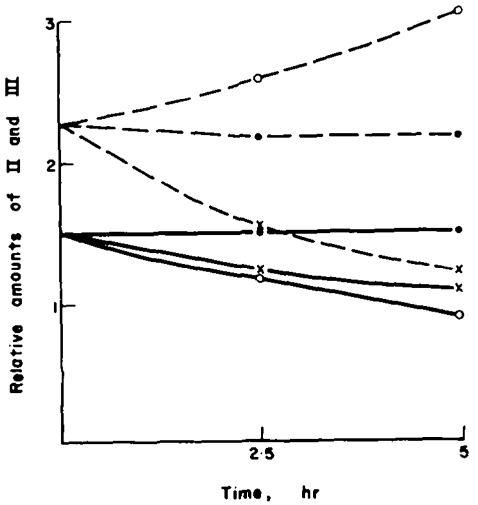
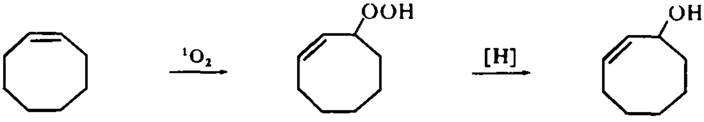


Fig 2. Changes of the relative amounts of II (———) and III (- - - - - -) in the photooxygenated mixture of I under various conditions: ○, irradiation under N_2; ●, standing at room temperature under N_2; ×, refluxing

scale model indicates that the hydroperoxy group and double bond of VIII are sufficiently close to interact transannularly.

Photosensitized oxygenation of cyclooctene (IX) in ethanol using methylene blue as sensitizer followed by reduction with sodium sulfite gave 2-cyclooctenol (X) in 40% yield. 1,5-Cyclooctadiene (I) and cyclooctene (IX) were competitively photooxygenated. Diene I was found to react seven times as fast as IX. It has been reported that singlet oxygen has an electrophilic nature and that thus it reacts faster with more electron-rich olefins.[2a, 5, 6] It is, therefore, considered that electron density of double bonds of I is increased more by the steric interaction than an isolated double bond of IX.



IX X

EXPERIMENTAL

All irradiations were made with an iodine lamp (visible light) in a reaction apparatus described previously.[7]

Photosensitized oxygenation of 1,5-*cyclooctadiene* (I). A soln of I (5·40 g; 0·05 mole) and rose bengal (500 mg) in 240 ml MeOH was irradiated under bubbling O_2 until 1·2 l. (0·05 mole) O_2 was consumed. The mixture was diluted with 200 ml water and treated with a soln of Na_2SO_3 (20 g) in 200 ml water under ice-cooling and stirring vigorously for 1 hr. The mixture was distilled under reduced pressure to give the first distillate (*ca* 200 ml), which contained some unreacted I, the second distillate (*ca* 200 ml) and the residue (A). The second distillate was extracted with light petroleum, then with ether. Evaporation of the extracts followed by vacuum distillation gave II (0·94 g; 16%) as an oil: b.p. 80° (bath temp)/2 mm; MS m/e 124 (M^+ peak); IR (neat) 3300, 2920, 1630, 1450, 1040 cm^{-1}; NMR (DMSO-d_6) τ 4·2–4·7 (m, 4H), 5·3 (d, J = 0·5 Hz, 1H), 5·2–5·4 (m, 1H), 7·1–7·3 (t, J = 0·6 Hz, 2H), 7·6–9·0 (m, 4H).

The residue (A) was extracted twice with ether. Evaporation of the extract followed by vacuum distillation gave III (0·84 g; 12%) as an oil: b.p. 120° (bath temp)/2 mm; MS m/e 140 (M^+ peak); IR (neat) 3350, 2900, 1695, 1650 (sh), 1100–1050 (broad), 920 cm^{-1}; NMR (CCl_4) τ 4·3–4·5 (m, 2H), 5·3–5·6 (m, 1H), 5·7 (s, 1H), 7·3–8·5 (m, 8H). (Found: C, 68·32; H, 8·80. Calc. for $C_8H_{12}O_2$: C, 68·54; H, 8·63%).

Catalytic hydrogenation of 2,5-*cyclooctadienol* (II) *and* 4-*hydroxy*-5-*cyclooctenone* (III). A soln of I (5·40 g; 0·05 mole) and methylene blue (50 mg) in 240 ml EtOH was photooxygenated and the mixture was treated as above to give crude II (1·31 g) and crude III (0·90 g) as oils which were almost pure by VPC analysis. A solution of II in 25 ml EtOAc was hydrogenated in the presence of Pt black (20 mg). Vacuum distillation of the product gave IV (1·06 g) as an oil: b.p. 70° (bath temp)/2 mm, lit.[8] b.p. 99°/16 mm; MS m/e 128 (M^+ peak): IR (neat) 3300. 2900. 1450. 1060. 990 cm^{-1}; NMR (CCl_4) τ 6·3 (m. 1H). 6·7 (s. 1H). 8·1–8·8 (m. 14H).

A soln of III in 25 ml EtOAc was hydrogenated in the same manner to give VI (0·82.g): b.p. 110° (bath temp)/2 mm, lit.[9] b.p. 100–102°/0·4–0·5 mm; MS m/e 142 (M^+ peak); IR (neat) 3380, 2925, 1690, 1450, 1350, 1060, 1000, 920 cm^{-1}; NMR (CCl_4) τ 5·4–5·7 (m, 1H), 6·0–6·5 (m, 1H), 7·6–8·8 (m, 12H). This compound was identical with an authentic sample*(IR).

Oxidation of cyclooctanol (IV). A soln of IV (0·64 g; 4·5 mmole) in 40 ml pyridine was added to chromic anhydride (1·50 g; 15 mmole) in 50 ml pyridine under ice-cooling. The mixture was allowed to stand at room temp for 20 hr and an excess MeOH was added. After 30 min the mixture was evaporated under reduced pressure and the residue was extracted twice with ether. Evaporation of the extract followed by vacuum distillation gave V as crystals: b.p. 88° (bath temp)/19 mm; m.p. 40–43°, lit.[10] m.p. 43·8; MS m/e 126 (M^+ peak); IR (neat) 2900, 1695, 1470–1440, 1330, 1200, 1150, 1100, 1060 cm^{-1}; NMR (CCl_4) τ 7·5–7·8 (m, 4H), 7·9–8·6 (m, 10H). This compound was identical with an authentic sample* (IR).

* The authors are indebted to Badische Anilin und Soda Fabrik, West Germany, for generous supply of these samples.

Oxidation of 4-hydroxycyclooctanone (VI). A soln of VI (225 mg; 1·7 mmole) in acetone was oxidized with Jones reagent as described.[11] Vacuum distillation of the product gave VII as an oil (76 mg; 34%): b.p. 110–120° (bath temp)/2 mm, lit.[12] b.p. 75–75·5°/1 mm; MS *m/e* 140 (M^+ peak); IR (neat) 2900, 1700, 1450, 1340, 1110 cm^{-1}; NMR (CCl_4) τ 7·3 (s, 4H), 7·65 (m, 4H), 8·15 (m, 4H).

A soln of VII (104 mg), semicarbazide hydrochloride (110 mg), and NaOAc (110 mg) in aqueous EtOH was allowed to stand overnight. Crystals deposited were collected and recrystallized from EtOH to give the monosemicarbazone (76 mg; 50%): m.p. 230° (dec). (Found: C, 47·17; H, 7·35. Calc. for $C_9H_{15}N_3O_2$: C, 47·23; H, 7·13%).

Determination of the ratio of II *to* III *during photooxygenation of* I. A soln of I (1·1 g) and rose bengal (300 mg) in 250 ml MeOH was irradiated under bubbling O_2. Aliquots were withdrawn from the soln at intervals. The aliquots were treated with triphenylphosphine in benzene to reduce VIII and analyzed by VPC (10% polyethylene glycol; 2·5 m × 0·3 cm column; temp 200°; carrier gas, He; 1 kg/cm^2; retention time, 4·9 min for II and 12·7 min for III). The results are shown in Fig 1.

Determination of the relative amounts of II *and* III *under various conditions.* The photooxygenated soln (243 ml) used for the determination of the ratio II/III in the above experiment was mixed with diphenylmethane (100 mg; as internal standard). Two 25 ml portions were taken up from the soln and treated under N_2 in following ways: (i) refluxing and (ii) standing at room temp. The remaining soln was irradiated (>350 mu) under N_2. Aliquots were withdrawn from these solns at intervals and after treatment with triphenylphosphine in benzene the relative amounts of II and III to diphenylmethane were determined by VPC. the results were shown in Fig 2.

Oxidation of 1,5-*cyclooctadiene* (I) *with chemically generated singlet oxygen.* To a soln of I (1·10 g; 10 mmole) in 200 ml MeOH was added 30% H_2O_2 (2.5 ml; 22.5 mmole). The mixture was cooled in an ice bath and 10% NaOCl aq (14 ml; 17 mmole) was added dropwise with stirring in the course of 1 hr. The mixture was treated with a soln of Na_2SO_3 (2·5 g) in 100 ml water under ice-cooling and stirring rapidly. About 100 ml of the solvent was evaporated under reduced pressure. The residue was diluted with water (200 ml) and extracted with ether. Evaporation of the dried ethereal extract gave an oil which was found to consist of only II by VPC analysis.

Photosensitized oxygenation of cyclooctene (IX). A soln of IX (5·50 g; 0·05 mmole) and methylene blue (100 mg) in 250 ml EtOH was irradiated under bubbling O_2. After 435 ml (0·019 mole) O_2 had been consumed, the mixture was treated in the same manner as in the case of I to give the first distillate (*ca* 200 ml), which contained some unreacted IX, the second distillate (*ca* 200 ml) and the residue. The second distillate and the residue were extracted with light petroleum and then with ether. Evaporation of the extracts followed by vacuum distillation gave X (1·05 g; 44% based on the consumed O_2) as an oil: b.p. 80° (bath temp 2 mm. lit.[13] b.p. 74°/2 mm; MS *m/e* 126 (M^+ peak); IR (neat) 3300, 2900, 1450, 1050, 990, 990, 745, 705 cm^{-1}; NMR (DMSO-d_6) τ 4.46 (d, $J = 12$ Hz, 1 H), 4.52 (d, $J = 12$ Hz, 1 H), 5·3 (d, $J = 9$ Hz, 1 H), 5·6 (m, 1 H), 8·0 (m, 2 H), 8·4–8·6 (m, 8 H).

Catalytic hydrogenation of 2-cyclooctenol (X). Hydrogenation of a soln of X (0·69 g) in 20 ml EtOAc with pt black (15 mg) proceeded readily. Working up of the mixture gave IV (0·59 g; 91%) which was identified by IR.

Determination of the relative reactivity of I *to* IX. 1,5-Cyclooctadiene I (1·1 g), cyclooctene IX (1·1 g), rose bengal (300 mg) and mesitylene (0·8 g; as internal standard) were dissolved in 250 ml MeOH. The soln was irradiated under bubbling O_2. Aliquots were withdrawn from the solution at intervals and analyzed by VPC. The relative rate was calculated from the relative amounts of the unreacted olefins.[5]

Reaction of cyclooctene (IX) *with* t-*butylhydroperoxide under irradiation.* A soln of IX (2·0 g; 0·018 mole) and t-butylhydroperoxide (2·0 g; 0·022 mole) in 250 ml MeOH was irradiated in the presence of rose bengal under bubbling N_2. The mixture was treated with a soln of Na_2SO_3 (20 g) in 400 ml water. After evaporation of the MeOH, the mixture was extracted with ether. Evaporation of the extract followed by vacuum distillation gave an oil (70 mg; 3%) which was identified as X by IR and VPC. No other product was detected.

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