103. Photochemical Reactions

151st Communication[1])

Photo-oxygenation of (*E*)- and (*Z*)-7-Methyl-β-ionone

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In memoriam David Ginsburg

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Photo-oxygenation of (*E*)-7-methyl-β-ionone ((*E*)-**1**) and (*E*)-8-methyl-β-ionone ((*E*)-**2**) gave rise to the formation of the hydroperoxy-enones (*E*)-**10** and (*E*)-**15**, respectively, which, in part, underwent intramolecular epoxidation to the hydroxy-epoxy-ketones **11** and **16**, respectively. The product distribution of the photo-oxidation of (*Z*)-**1** shows a marked influence of the skewed ground-state conformation of the dienone chromophore. Thus, singlet oxygen ($^1O_2$) was added to C(γ) of the dienone chromophore leading to the spirocyclic peroxy-hemiacetal **12** and to the endoperoxide **13**. In addition, the tricyclic peroxide **14** was formed as a new type of product *via* primary addition of $^1O_2$ to C(δ) of the dienone chromophore. The structure of **14** was established by X-ray crystal-structure analysis of the hemiacetal **22**.

1. Introduction. – Singlet oxygen ($^1O_2$) is known to react with different types of compounds, giving rise to a variety of oxygenated products [2–5]. The reactions of $^1O_2$ with conjugated dienoids typically fall into one of three categories depending on the ground-state configuration of the compounds: [2 + 2] cycloaddition to form dioxetanes, [4 + 2] cycloaddition giving endoperoxides and the 'ene' reaction yielding allylic hydroperoxides.

In the course of our investigations of the photochemical reactivity in the ionone series, we found that the β-substituent in the dienone (*E*)-**1** *(Scheme 1)* showed a significant influence on its behavior [1] [6], while the α-Me substituent in the dienone (*E*)-**2** *(Scheme 2)* had little effect [7]. Thus, photolysis ($\lambda > 347$ nm) of 7-methyl-β-ionone ((*E*)-**1**[5]) causes rapid (*E*/*Z*)-isomerization and subsequent formation of **3** representing a new type of compound [6]. In contrast to (*Z*)-8-methyl-β-ionone ((*Z*)-**2**) and (*Z*)-β-ionone ((*Z*)-**4**), which cyclize thermally as well as photochemically to the pyran **5** [7] and **6** [9][6]), respectively, the 7-Me analog (*Z*)-**1** is stable at room temperature [6]. The main reason for the

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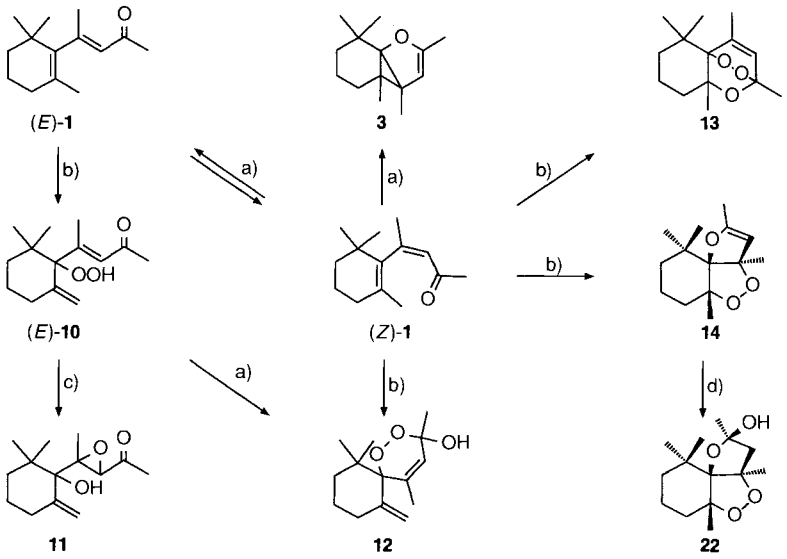
[4]) X-Ray analysis.

[5]) Numbering according to the carotenoid nomenclature [8].

[6]) Below −50°, (*Z*)-**4** could be detected [9].

Scheme 1



a) $\lambda > 280$ nm, pentane or MeCN; b) $^1O_2$, MeOH; c) KOH, MeOH; d) oxalic acid, H_2O, THF.

difference of this photochemical reactivity between (*E*)-**1** and (*E*)-**2** or (*E*)-**4** can be found in the hindered rotation of the side chain in (*E*)- and (*Z*)-**1** due to steric interaction of the 7-Me group with the Me groups of the cyclohexene ring, as is demonstrated in NMR experiments [10].

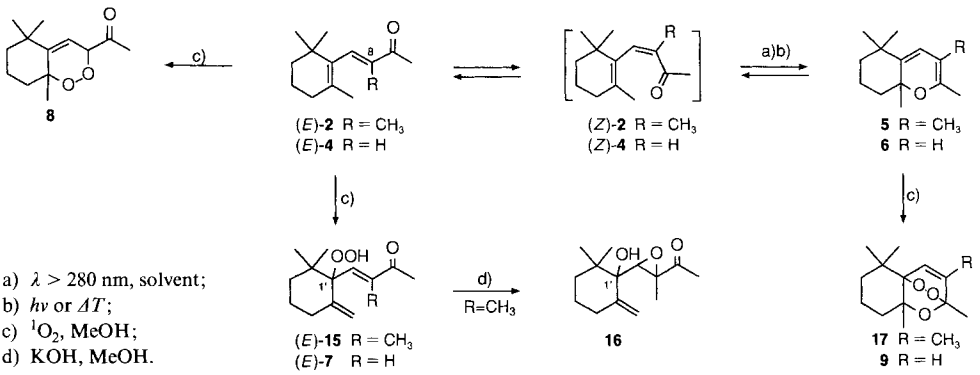
It has been reported by *Mousseron-Canet et al.* [11] that β-ionone ((*E*)-**4**) reacts readily with $^1O_2$ to give the hydroperoxide (*E*)-**7** and several transformation products of the unstable endoperoxide **8**. Furthermore, *Ina* and coworkers [12] described the photo-oxidation of the pyran **6** leading to the endoperoxide **9** *(cf. Scheme 2)*.

Since the photochemical behavior of 7-methyl-β-ionone (*E*)-**1** shows the strong influence of the skewed ground-state conformation of the dienone chromophore, it seemed to be attractive to investigate the photo-oxygenation of 7- and 8-methyl-β-ionone (*E*)-**1** and (*E*)-**2**, respectively, in relation to that of β-ionone ((*E*)-**4**). By examining the effect of the substituents of the enone side chain, we hoped to see, whether the reactivity with $^1O_2$ also depends on the ground-state conformation of the dienone chromophore.

2. Photolyses. – Photo-oxygenation of (*E*)-**1** (40% conversion)[7]) in MeOH with *Rose Bengal* as a sensitizer and a catalytic amount of KOH using a Hg medium-pressure lamp filtered through $Na_2Cr_2O_7$ gave (*E*)-**10** (65%), and **11** (19%). Photo-oxygenation of (*Z*)-**1** under the same conditions (70% conversion) yielded[7]) **12** (19%), **13** (37%), and **14** (15%; *Scheme 1*). Photo-oxygenation of (*E*)-**2** with *Rose Bengal* in MeOH (95% conversion)[7]) afforded **15** (53%), and **16** (7%). The pyran **5** (100% conversion) furnished **17** (35%; *Scheme 2*).

[7]) Yields are based on converted starting material.

Scheme 2

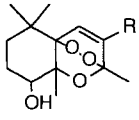


3. Structure of the Products. – The structures of all new photoproducts were deduced from their spectral data. Only the most relevant data are discussed below, together with decisive chemical transformations which confirmed the assigned structures. For full spectral data and the NMR assignments, see *Exper. Part.*

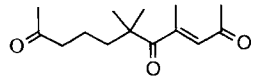
Hydroperoxy-enones (*E*)-**10** *and* (*E*)-**15**, *and Epoxy-ketones* **11** *and* **16** (*Schemes 1* and *2*). The enone chromophore of (*E*)-**10** and (*E*)-**15** is evidenced by the UV maxima at 238 and 228 nm as well as by the IR bands at 1685 and 1677 cm^{-1}, respectively. In the ^{13}C-NMR spectra, the signals of the quaternary C(1')-atoms bearing the hydroperoxy group are at 94.8 ppm and 91.5 ppm for (*E*)-**10** and (*E*)-**15**, respectively, and they are shifted upfield by 12–16 ppm for the C(1')-OH in the spectra of the epoxy-ketones **11** and **16** as well as of the reduction product (*E*)-**18**[8]). On treatment of the hydroperoxy-enone (*E*)-**10** with KOH in MeOH an intramolecular epoxidation led to the epoxy-ketone **11** (83%).

Dioxaspiro[5.5]undecenol **12** *(Scheme 1).* The structure of this hemiacetal of the hydroperoxy-enone (*Z*)-**10** was established by the phototransformation of (*E*)-**10** to **12** (see *Exper. Part*).

Trioxatricyclo[6.2.2.0^{1,6}]dodecenes **13** *(Scheme 1) and* **17** *(Scheme 2).* Their structures were derived by comparison of their spectra with those of the previously described analogs **19** and **20** [13] and the acid-catalyzed conversion of **13** to the known triketone **21** [14].



19 R=CH3
20 R=H



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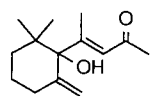
Trioxatricyclo[6.4.0.0^{1,5}]dodecene **14** *(Scheme 1).* The structure was elucidated on the basis of the spectral data. Thus, the strong IR band at 1682 cm^{-1} as well as a *s* and a *d* at 159.0 and 101.4 ppm, respectively, in the ^{13}C-NMR spectrum are characteristic of an

[8]) The hydroxy-enone (*E*)-**18** was obtained by reduction of (*E*)-**10** with Ph_3P in CH_2Cl_2.



enol-ether moiety. Furthermore, in the ^{13}C-NMR spectrum, there are 3 *s* at 102.3, 98.5, and 88.4 ppm corresponding to three O-substituted quaternary C-atoms. The enol-ether moiety is very acid-sensitive, and **14** was, therefore, converted to the hemiacetal **22** *(Scheme 1)* which was subjected to X-ray analysis for final confirmation of the structure and assignment of the configuration.

X-Ray Analysis of 22 *(Fig.).* – *(1*RS,*3*RS,*5*RS,*8*RS*)-3,5,8,12,12-Pentamethyl-2,6,7-trioxatricyclo-[6.4.0.0^{1,5}]dodecan-3-ol* (**22**). Formula: $C_{14}H_{24}O_4$; mol.-wt. = 256.34, monoclinic space group $P2_1/c$, molecules in the asymmetric unit: $Z = 2$, with cell dimensions $a = 16.343(7)$, $b = 12.858(3)$, $c = 15.038$ Å, $\alpha = 90.00(0)$,

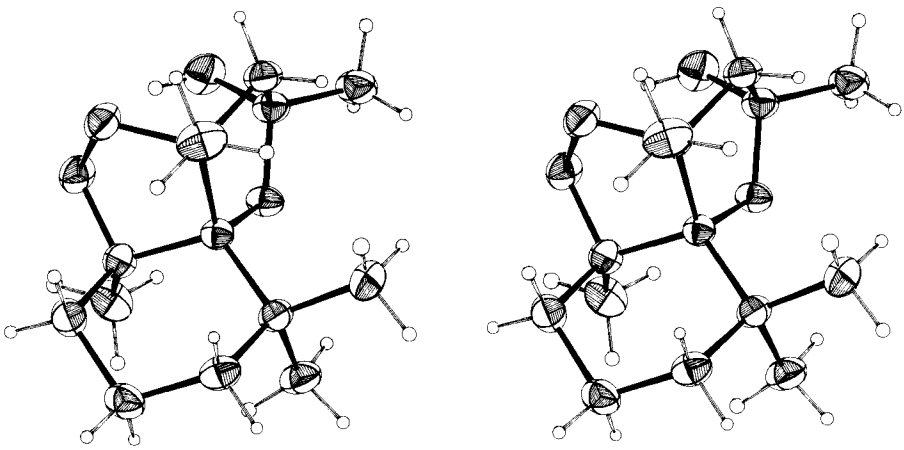


Figure. *Stereographic view of* **22**. Vibrational ellipsoids at the 50% level, ORTEP [18].

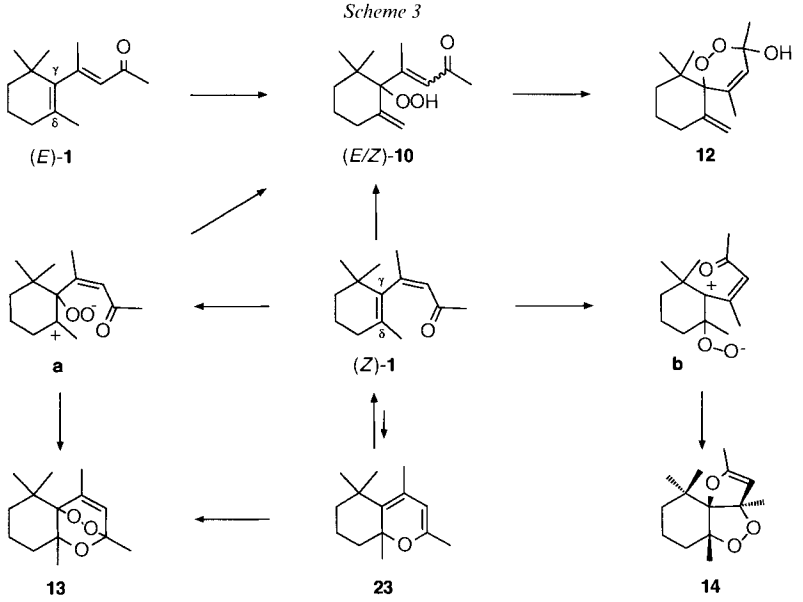
$\beta = 118.26(3)$, $\gamma = 90.00(0)°$. Intensities were measured at room temperature with an *Enraf Nonius CAD4* diffractometer equipped with a graphite monochromator (Mo$K\alpha$, $\lambda = 0.7107$ Å). Of the 4848 independent reflections ($\theta > 25°$), 2639 with $I > 3\sigma(I)$ were used in the refinement. The structure was solved by direct methods with MULTAN 80 [15] and refined by full-matrix least-squares analysis (SHELX76 [16], XRAY72 [17]). The refinement converged at $R = 0.046$, $R_w = 0.052$. Atomic positional and anisotropic displacement parameters (H-atoms isotropic) are deposited with the *Cambridge Crystallographic Data Centre*, Lensfield Road, Cambridge CB2 1EW, England.

4. Discussion. – Photo-oxygenation of (*E*)-7-methyl-β-ionone ((*E*)-**1**) yielded the hydroperoxy-enone (*E*)-**10** as the main product. It is formed *via* an 'ene' reaction involving a regioselective attack of $^1O_2$ at C(γ) of the dienone chromophore (see *Scheme 3*). Thus, (*E*)-**1** shows the same behavior as (*E*)-8-methyl-β-ionone ((*E*)-**2**) and β-ionone ((*E*)-**4**) which gave the corresponding hydroperoxides (*E*)-**15** and (*E*)-**7** [11], respectively *(Scheme 2)*. In addition, the α,β-epoxy-γ-hydroxy-ketones **11** and **16** were obtained as secondary products by intramolecular epoxidation of the hydroperoxy-enones (*E*)-**10** and **15**, respectively. Endoperoxides analogous to **8** *(Scheme 2)*, however, arising from [2 + 4] addition of $^1O_2$ and the diene moiety, were not detected on photo-oxygenation of (*E*)-**1** and (*E*)-**2**.

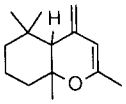
(*Z*)-7-Methyl-β-ionone ((*Z*)-**1**) also underwent an 'ene' reaction with $^1O_2$ leading to the hydroperoxy-enone (*Z*)-**10** which cyclized to the hemiacetal **12** *(Scheme 3)*. This compound was also obtained on photolysis of (*E*)-**10** ($\lambda > 347$ nm).

Since the pyran **23** *(Scheme 3)* was not detected on photolysis of (*E*/*Z*)-**1**, it was surprising to find the endoperoxide **13** as the main photo-oxidation product of (*Z*)-**1**. For the formation of **13**, $^1O_2$ could react in a [2 + 4] cycloaddition with the pyran **23** present in small amounts in an equilibrium with (*Z*)-**1**. Alternatively, **13** may be formed *via* the intermediate **a** which could either cyclize to **13** or undergo an intramolecular H abstraction leading to (*Z*)-**10** *(Scheme 3)*.

Scheme 3



The most interesting product of the photo-oxygenation of (*Z*)-**1** is the tricyclic peroxide **14**. It is an addition product of $^1O_2$ to C(β) and C(δ) of the dienone moiety. In competition with the attack of $^1O_2$ at the sterically hindered C(γ), addition of $^1O_2$ to C(δ) of the tetrasubstituted dienone C=C bond, which is in an orthogonal arrangement in relation to the enone moiety [6], can occur. Cyclization *via* intermediate **b** – or in a synchronous process – leads to **14** *(Scheme 3)*. The tricyclic peroxide **14** is structurally closely related to the photocyclization product **3** *(Scheme 1)* obtained on photolysis of (*Z*)-**1**. Both arise *via* an uncommon bond formation between the C=O O-atom and C(γ) instead of the more usual C(δ) due to the twisted ground-state conformation of (*Z*)-**1** with the (*Z*)-enone side chain orthogonal to the cyclohexene moiety [6]. It seems that product formation involving a cyclization with bond formation between the C=O O-atom and C(δ) is only observed in cases where C(γ) is transformed from an sp^2 to a bridgehead sp^3 center, which releases the repulsive interaction between the β-Me group and the *gem.*-Me groups. Thus, pyran **23** was not detected on photolysis of (*Z*)-**1** in neutral media, whereas on irradiation in the presence of catalytic amounts of acid, the ether **24**, analogous to **23**, was obtained, in which the bridgehead C(γ) center is sp^3 carrying an H-atom and the C=C bond is exocyclic [6]. Also on photo-oxygenation of (*Z*)-**1**, bond formation between the C=O O-atom and C(δ) is coupled with the transformation of C(γ) into an sp^3 center resulting in the endoperoxide **13**.



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In conclusion, the present investigation demonstrates that the product distribution of the photo-oxygenation of (*Z*)-7-methyl-β-ionone ((*Z*)-**1**) is governed by the ground-state conformation of the dienone chromophore, giving rise to a new type of product, whereas (*E*)-**1** shows the same behavior as (*E*)-**2** and (*E*)-**4**.

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Experimental Part

General. See [19] except as noted below. Column chromatography (CC) was carried out on silica gel *60 Merck* 0.040–0.063 mm, 230–400 mesh ASTM (SiO_2) according to [20] (flash chromatography). Anal. pure samples were obtained, in general, after repeated CC on SiO_2. ^{1}H-NMR spectra were taken on a *Bruker WP-80 CW* (80 MHz) or *WM 300* (300 MHz) instrument in $CDCl_3$ solns. or on a *Varian HA-100* (100 MHz) instrument in $CDCl_3$ or CCl_4 solns. (as indicated below). Photolysis experiments were carried out using a 125-W Hg medium-pressure lamp [19]. $Na_2Cr_2O_7$ filter soln. ($\lambda > 540$ nm): sat. aq. $Na_2Cr_2O_7/H_2O$ 1:10; $Pb(NO_3)_2$/NaBr filter soln. ($\lambda > 347$ nm): NaBr (750 g) and $Pb(NO_3)_2$ (9 g) in H_2O (1000 ml). MeOH *(Fluka)* was distilled from *Komplexon III*.

1. Photolyses. – 1.1. *Photo-oxygenation of* (E)-**1**. A soln. of (*E*)-**1** (1.00 g, 4.85 mmol) and Rose Bengal (500 mg, 0.49 mmol) in MeOH (180 ml) and a cat. amount of KOH was irradiated (125-W Hg medium-pressure lamp, Na_2Cr_2O filter) for 17 h bubbling O_2 through the soln. The solvent was evaporated under reduced pressure at 0° to r.t. and the residue filtered through SiO_2 washing with Et_2O. CC (hexane/Et_2O 3:1) afforded (*E*)-**1** (609 mg)[7]), (*E*)-**10** (292 mg, 65%), and **11** (85 mg, 19%).

(E)-4-(1'-Hydroperoxy-2',2'-dimethyl-6'-methylidenecyclohexyl)pent-3-en-2-one ((*E*)-**10**). M.p. 89–90°. UV (0.220 mg in 10 ml of pentane): 238 (8400). IR: 3550–3200*w* (br.), 3100*w*, 2980*m* (sh), 2935*s*, 2870*m*, 1685*s*, 1635*w*, 1600*s*, 1480*w*, 1460*m*, 1433*m*, 1388*m*, 1378*m*, 1365*m*, 1353*s*, 1325*m*, 1285*w*, 1195*s*, 1163*w*, 1070*w*, 1050*w*, 1015*w*, 963*w*, 923*m*, 835*w*, 873*w*, 852*w*. ^{1}H-NMR (300 MHz): 0.88, 1.00 (2*s*, 2 CH_3–C(2')); 0.8–2.5 (*m*, 2 H–C(3')); 5.27 (2*m*, $w_{1/2} = 4$, CH_2=C(6')); 6.34 (*m*, $w_{1/2} = 3$, H–C(3)); 7.36 (*s*, OOH). ^{13}C-NMR (75 MHz): 20.6, 25.1, 26.2, 32.7 (4*q*, C(1), C(5), 2 CH_3–C(2')); 21.5, 32.7, 37.1 (3*t*, C(3'), C(4'), C(5')); 39.7 (*s*, C(2')); 94.8 (*s*, C(1')); 117.7 (*t*, CH_2=C(6')); 128.0 (*d*, C(3)); 142.7, 153.9 (2*s*, C(4), C(6')); 199.3 (*s*, CO). MS: 238 (< 1, $M^{+\cdot}$, $C_{14}H_{22}O_3$), 221 (3), 179 (9), 137 (15), 123 (10), 111 (13), 109 (21), 95 (12), 91 (9), 81 (8), 69 (49), 67 (11), 55 (19), 53 (11), *43* (100), 41 (33). Anal. calc. for $C_{14}H_{22}O_3$ (238.33): C 70.56, H 9.30; found: C 70.46, H 9.40.

3,4-Epoxy-4-(1'-hydroxy-2,2'-dimethyl-6'-methylidenecyclohexyl)pentan-2-one (**11**). M.p. 69–70° (hexane). UV (2.08 mg in 2 ml of MeCN): 290 (32). IR: 3590*w*, 3545*m*, 3500*m* (sh), 3095*w*, 2990*s*, 2975*s*, 2940*s*, 2930*s* (sh), 2870*s*, 1725*s*, 1710*s*, 1685*s*, 1635*m*, 1600*m*, 1460*s*, 1420*m* (br.), 1390*m* (sh), 1375*s*, 1365*s*, 1350*s*, 1315*m*, 1285*m*, 1230*m*, 1210*m*, 1195*m*, 1185*m*, 1160*m*, 1120*w*, 1090*m*, 1075*m*, 1050*s*, 1005*m*, 985*s*, 960*m*, 930*w*, 915*s*, 890*w*, 875*w*, 860*w*. ^{1}H-NMR (100 MHz, $CDCl_3$): 1.03, 1.06 (*s*, 2 CH_3–C(2')); 1.42 (*s*, 3 H–C(5)); 1.97 (*s*, OH); 2.21 (*s*, 3 H–C(1)); 0.8–2.7 (*m*, 2 H–C(3'), 2 H–C(4'), 2 H–C(5')); 3.95 (*s*, H–C(3)); 5.01 (*m*, $w_{1/2} = 6$, CH_2=C(6')). ^{13}C-NMR: 19.1, 24.9, 25.7, 28.2 (4*q*, C(1), C(5), 2 CH_3–C(2')): 21.4, 33.0, 38.2 (3*t*, C(3'), C(4'), C(5')); 37.8 (*s*, C(2')); 62.0 (*d*, C(3)); 64.7 (*s*, C(4)); 78.9 (*s*, C(1')); 111.9 (*t*, CH_2=C(6')); 147.0 (*s*, C(6')); 205.4 (*s*, C(2)). MS: 238 (< 1, $M^{+\cdot}$, $C_{14}H_{22}O_3$), 233 (0.4), 196 (6), 195 (6), 139 (10), 109 (12), 99 (11), 95 (30), 85 (23), 69 (22), 55 (12), *43* (100), 41 (20). Anal. calc. for $C_{14}H_{22}O_3$ (238.33): C 70.56, H 9.30; found: C 70.20, H 9.24.

1.2. *Photo-oxygenation of* (Z)-**1**. A soln. of (*Z*)-**1** (1.00 g, 4.85 mmol), *Rose Bengal* (300 mg, 0.29 mmol), and KOH (*ca.* 100 mg) in MeOH (150 ml) was irradiated (125-W Hg medium-pressure lamp, $Na_2Cr_2O_7$ filter) for 12 h bubbling O_2 through the soln. The solvent was evaporated, and CC (hexane/AcOEt/CH_2Cl_2 19:1:19) of the mixture afforded (*Z*)-**1** (300 mg), **12** (150 mg, 19%), **13** (300 mg, 37%), and **14** (120 mg, 15%).

3,5,7,7-Tetramethyl-11-methylidene-1,2-dioxaspiro[5.5]undec-4-en-3-ol (**12**). M.p. 72–74° (pentane). IR: 3600*m*, 3460*w* (br.), 3080*w*, 3030*w* (sh), 2990*s* (sh), 2970*s* (sh), 2940*s*, 2870*s*, 1750*w*, 1655*w*, 1640*w*, 1460*m* (sh), 1440*m*, 1380*s*, 1365*m*, 1355*m*, 1315*m*, 1285*w*, 1270*w*, 1225*m*, 1180*w*, 1135*s*, 1080*m*, 1065*m*, 1045*w*, 1030*w*, 995*w*, 970*w*, 960*w*, 940*w*, 922*m*, 904*s*, 883*w*, 867*w*, 852*w*. ^{1}H-NMR (100 MHz, CCl_4): 0.94, 1.11, 1.17 (3*s*, 2 CH_3–C(7), CH_3–C(3)); 1.85 (*d*, J = 1.5, CH_3–C(5)); 0.8–2.8 (*m*, 2 H–C(8), 2 H–C(9), 2 H–C(10)); 2.68 (*m*, $w_{1/2}$ = 3, OH); 4.66, 4.93 (2*m*, $w_{1/2}$ = 5, CH_2=C(11)); 5.57 (*q*, J = 1.5, H–C(4)). ^{13}C-NMR: 22.8, 23.0, 24.7, 26.5 (4*q*, 4 CH_3); 21.9, 31.6, 37.7 (3*t*, C(8), C(9), C(10)); 38.8 (*s*, C(7)); 88.4, 96.5 (2*s*, C(3), C(6)); 113.2 (*t*, CH_2=C(11)); 129.0 (*d*, C(4)); 137.8, 146.7 (2*s*, C(5), C(11)). MS: 238 (< 1, M^+, $C_{14}H_{22}O_3$), 220 (2), 205 (12), 163 (20), 135 (19), 123 (28), 121 (21), 112 (18), 111 (18), 109 (61), 107 (22), 95 (29), 93 (22), 91 (24), 85 (18), 82 (16), 81 (29), 79 (27), 77 (20), 69 (75), 67 (29), 55 (39), 53 (26), *43* (100), 41 (85). Anal. calc. for $C_{14}H_{22}O_3$ (238.33): C 70.56, H 9.30; found: C 70.45, H 9.12.

2,2,6,8,11-Pentamethyl-7,9,10-trioxatricyclo[6.2.2.0^{1,6}]dodec-11-ene (**13**). B.p. 105°/0.05 Torr. IR: 3040*w*, 2995*s*, 2975*s*, 2940*s*, 2870*s*, 1685*w*, 1645*w*, 1600*w*, 1460*s*, 1445*s*, 1395*m*, 1380*s*, 1370*s*, 1330*m*, 1300*w*, 1280*m*, 1260*m*, 1225*w*, 1200*s*, 1162*m*, 1149*m*, 1118*s*, 1100*s*, 1073*w*, 1052*w*, 1039*w*, 1022*w*, 990*m*, 960*s*, 935*m*, 925*m*, 905*m*, 877*m*, 861*s*. ^{1}H-NMR (100 MHz, CCl_4): 1.02, 1.10, 1.22, 1.29 (4*s*, 2 CH_3–C(2), CH_3–C(6), CH_3–C(8)); 0.9–2.2 (*m*, 2 H–C(3), 2 H–C(4), 2 H–C(5)); 2.08 (*d*, J = 2, CH_3–C(11)); 5.98 (*q*, J = 2, H–C(12)). ^{13}C-NMR: 21.0, 21.0, 25.3, 25.6, 27.2 (5*q*, 5 CH_3); 19.2, 35.8, 38.4 (3*t*, C(3), C(4), C(5)); 37.0 (*s*, C(2)); 77.8, 84.6, 95.0 (3*s*, C(1), C(6), C(8)); 130.3 (*d*, C(2)); 139.2 (*s*, C(11)). MS: 238 (3, M^+, $C_{14}H_{22}O_3$), 223 (1), 206 (3), 191 (17), 154 (11), 153 (14), 127 (15), 123 (20), 112 (55), 111 (12), 109 (56), 81 (16), 71 (11), 69 (70), 67 (10), 55 (14), *43* (100), 41 (32). Anal. calc. for $C_{14}H_{22}O_3$ (238.33): C 70.56, H 9.30; found: C 70.70, H 9.28.

(1RS,5RS,8RS)-3,5,8,12,12-Pentamethyl-2,6,7-trioxatricyclo[6.4.0.0^{1,5}]dodec-3-ene (**14**). UV (0.919 mg in 25 ml of pentane): 210 (5500). IR: 3000*m*, 2985*m*, 2960*s*, 2940*s*, 2875*m*, 1682*s*, 1480*w*, 1468*m*, 1460*m*, 1445*m*, 1435*m* (sh), 1390*m*, 1380*s*, 1374*s*, 1339*m*, 1317*s*, 1300*m*, 1275*w*, 1247*s*, 1230*w*, 1190*w*, 1170*w*, 1145*m*, 1110*m*, 1065*m*, 1050*m*, 1035*m*, 1022*s*, 982*m*, 971*m*, 940*m*, 910*m*, 875*w*, 840*w*. ^{1}H-NMR (100 MHz, $CDCl_3$): 0.98, 1.11 (2*s*, 2 CH_3–C(12)); 1.30 (*s*, CH_3–C(8)); 1.60 (*s*, CH_3–C(5)); 1.83 (*d*, J = 1.5, CH_3–C(3)); 0.9–2.3 (*m*, 2 H–C(9), 2 H–C(10), 2 H–C(11)); 4.52 (*m*, $w_{1/2}$ = 3, H–C(4)). ^{13}C-NMR (*ca.* 90% pure): 13.5, 18.8, 20.1, 25.2, 25.9 (5*q*, 5 CH_3); 18.7, 33.7, 37.4 (3*t*, C(9), C(10), C(11)); 38.1 (*s*, C(12)); 88.4, 98.5, 102.3 (3*s*, C(1), C(5), C(8)); 101.4 (*d*, C(4)); 158.9 (*s*, C(3)). MS: 238 (19, M^+, $C_{14}H_{22}O_3$), 206 (5), 195 (15), 191 (36), 153 (12), 123 (13), 112 (35), 111 (38), 109 (21), 99 (10), 95 (13), 81 (11), 69 (38), 55 (19), *43* (100), 41 (25). Anal. calc. for $C_{14}H_{22}O_3$ (238.33): C 70.56, H 9.30; found: C 70.49, H 9.24.

1.3. *Photo-oxygenation of (*E*)-***2***.* A soln. of (*E*)-**2** (1.0 g, 4.85 mmol), *Rose Bengal* (500 mg, 0.49 mmol), and a cat. amount of KOH in MeOH (250 ml) was irradiated as described in *1.1* for 15 h. Workup and CC (benzene AcOEt 9:1) afforded (*E*)-**2** (470 mg), (*E*)-**15** (325 mg, 53%), and **16** (45 mg, 7%).

*(*E*)-4-(1′-Hydroperoxy-2′,2′-dimethyl-6′-methylidenecyclohexyl)-3-methylbut-3-en-2-one* ((*E*)-**15**). M.p. 99–100° (Et_2O/pentane). UV (0.542 mg in 26 ml of pentane): 228 (8300). IR: 3520*w*, 3090*w*, 2970*m*, 2940*m*,, 2870*m*, 1677*s*, 1638*w*, 1475*w* (sh), 1460*m*, 1440*m*, 1388*m*, 1365*m*, 1335*m* (br.), 1253*m*, 1235*w*, 1213*w*, 1165*w*, 1060*w*, 1005*w*, 970*w*, 910*m*, 895*w*. ^{1}H-NMR (100 MHz, $CDCl_3$): 0.93, 0.96 (2*s*, 2 CH_3–C(2′)); 1.0–2.6 (*m*, 2 H–C(3′), 2 H–C(4′), 2 H–C(5′)); 2.08 (*d*, J = 1.5, CH_3–C(3)); 2.34 (*s*, 3 H–C(1)); 5.00, 5.22 (2*m*, $w_{1/2}$ = 4, CH_2=C(6′)); 6.76 (*m*, $w_{1/2}$ = 4, H–C(4)); 7.48 (*s*, OOH). ^{13}C-NMR: 12.2, 24.7, 24.8, 26.2 (4*q*, 4 CH_3); 22.7, 32.3, 36.4 (3*t*, C(3′), C(4′), C(5′)); 41.7 (*s*, C(2′)); 91.5 (*s*, C(1′)); 114.7 (*t*, CH_2=C(6′)); 138.7 (*d*, C(4)); 139.7, 136.8 (2*s*, C(3), C(6′)); 201.0 (*s*, C(2)). MS: 238 (1, M^+, $C_{14}H_{22}O_3$), 222 (5), 221 (13), 220 (2), 205 (3), 179 (15), 137 (12), 112 (15), 111 (40), 109 (23), 95 (13), 81 (10), 89 (30), 67 (14), 55 (17), 53 (10), *43* (100), 41 (32). Anal. calc. for $C_{14}H_{22}O_3$ (238.33): C 70.56, H 9.30; found: C 70.63, H 9.25.

3,4-Epoxy-4-(1′-hydroxy-2′,2′-dimethyl-6′-methylidenecyclohexyl)-3-methylbutan-2-one (**16**). B.p. 85°/0.1 Torr. UV (2.618 mg in 10 ml of pentane): 275 (sh, 190), 285 (sh, 120). IR: 2555*m*, 3080*w*, 2940*s*, 2870*m*, 1715*s*, 1668*w*, 1650*w*, 1470*m*, 1450*m*, 1420*m*, 1388*m*, 1367*m* (sh), 1360*m*, 1335*w*, 1307*m*, 1270*m*, 1212*w*, 1153*m*, 1095*w*, 1060*m*, 1025*w*, 995*w*, 973*w*, 932*w*, 912*s*, 885*w*, 855*m*. ^{1}H-NMR (100 MHz, $CDCl_3$): 0.94, 1.02 (2*s*, 2 CH_3–C(2′)); 1.52 (*s*, CH_3–C(3)); 1.3–2.5 (*m*, 2 H–C(3′), 2 H–C(4′), 2 H–C(5′)); 2.09 (*s*, 3 H–C(1)); 2.28 (*s*, OH); 3.32 (*s*, H–C(4)); 4.88 (*m*, $w_{1/2}$ = 3, CH_2=C(6′)). ^{13}C-NMR: 11.8, 22.3, 23.7, 24.0 (4*q*, 4 CH_3); 22.9, 33.2, 37.2 (3*t*, C(3′), C(4′), C(5′)); 41.2 (*s*, C(2′)); 60.2 (*d*, C(4)); 63.9, 75.5 (2*s*, C(3), C(1′)); 109.1 (*t*, CH_2=C(6′)); 145.9 (*s*, C(6′)); 207.1 (*s*, C(2)). MS: 238 (6, M^+, $C_{14}H_{22}O_3$), 205 (3), 195 (6), 137 (19), 123 (10), 109 (24), 99 (10), 96 (10), 95 (24), 85 (31), 81 (17), 79 (10), 77 (1), 69 (40), 67 (17), 55 (26), 53 (15), *43* (100), 41 (48). Anal. calc. for $C_{14}H_{22}O_3$ (238.33): C 70.56, H 9.30; found: C 70.72, H 9.39.

1.4. *Photo-oxygenation of* **5**. A soln. of **5** [7] (250 mg, 1.2 mmol) and *Rose Bengal* (6 mg, 0.006 mmol) in MeOH (15 ml) was irradiated as described in *1.1* for 3 h. Workup and CC (hexane/AcOEt 9:1) gave **17** (100 mg, 35%).

2,2,6,8,12-Pentamethyl-7,9,10-trioxatricyclo[6.2.2.0^{1,6}]dodec-11-ene (**17**). M.p. 59–61° (pentane). IR: 3045*w*, 3000*m*, 2960*s*, 2938*s*, 2870*s*, 1725*w*, 1670*w*, 1475*m* (sh), 1460*m* (sh), 1452*m*, 1435*m*, 1390*m*, 1382*m*, 1372*m*, 1330*w*, 1286*w*, 1242*m*, 1210*w*, 1190*m*, 1168*w*, 1125*s*, 1092*m*, 1068*w*, 1030*w* (br.), 981*m*, 960*s*, 920*m*, 885*w*, 872*w*, 861*w*. ^{1}H-NMR (100 MHz, $CDCl_3$): 0.98, 1.07, 1.08 (3*s*, 2 CH_3–C(2), CH_3–C(6)); 1.41 (*s*, CH_3–C(8)); 1.89 (*d*, $J = 2$, CH_3–C(12)); 0.9–2.4 (*m*, 2 H–C(3), 2 H–C(4), 2 H–C(5)); 6.14 (*q*, $J = 2$, H–C(11)). ^{13}C-NMR: 16.7, 18.4, 24.4, 25.5, 26.6 (5*q*, 5 CH_3); 19.4, 34.6, 34.6 (3*t*, C(3), C(4), C(5)); 35.6 (*s*, C(2)); 75.8, 82.6, 96.9 (3*s*, C(1), C(6), C(8)); 122.4 (*d*, C(11)); 140.9 (*s*, C(12)). MS: 238 (12, M^+, $C_{14}H_{22}O_3$), 206 (18), 192 (11), 191 (75), 153 (23), 137 (6), 127 (25), 123 (18), 112 (34), 111 (21), 109 (37), 95 (13), 85 (22), 81 (15), 55 (20), *43* (100), 41 (33). Anal. calc. for $C_{14}H_{22}O_3$ (238.33): C 70.56, H 9.30; found: C 70.55, H 9.37.

1.5. *Photolysis of* (E)-**10**. A soln. of (*E*)-**10** (60 mg, 0.25 mmol) in MeCN (7 ml) was irradiated (125-W Hg medium-pressure lamp, $Pb(NO_3)_2$/NaBr filter) for 1 h. The solvent was evaporated and the residue chromatographed (CH_2Cl_2/AcOEt 19:1) affording **12** (25 mg, 42%).

2. Additional Experiments. – 2.1. *Transformation of* (E)-**10** *into* **11**. A soln. of (*E*)-**10** (40 mg, 0.17 mmol) and KOH (*ca.* 10 mg) in MeOH (10 ml) was stirred at 50° overnight. The mixture was concentrated, and CC (hexane/Et_2O 3:1) afforded **11** (31 mg, 83%).

2.2. *Reduction of* (E)-**10**. A mixture of (*E*)-**10** (292 mg, 1.23 mmol), Ph_3P (1.5 g, 5.7 mmol) in CH_2Cl_2 (10 ml) was stirred at r.t. overnight. CC (hexane/Et_2O 3:1) gave (*E*)-**18** (264 mg, 96%).

(E)-4-(1′-Hydroxy-2′,2′-dimethyl-6′-methylidenecyclohexyl)pent-3-en-2-one ((*E*)-**18**). M.p. 57–58° (pentane). UV (0.135 mg in 5 ml of pentane): 237 (11 200). UV (1.957 mg in 2 ml of pentane): 333 (60). IR: 3590*m*, 3470*w* (br.), 3090*w*, 3020*w*, 2980*s*, 2940*s*, 2860*s*, 1685*s*, 1625*m*, 1595*s*, 1475*m*, 1455*m*, 1445*m*, 1430*s*, 1382*s*, 1370*s*, 1360*s*, 1350*s*, 1287*m*, 1220*m*, 1195*s*, 1155*m*, 1045*m*, 1010*m*, 972*m*, 960*s*, 940*m*, 930*m*, 910*s*, 885*w*, 850*m*. ^{1}H-NMR (300 MHz): 0.91, 1.03 (2*s*, 1.03 (2*s*, 2 CH_3–C(2′)); 1.60 (*s*, OH); 1.34–1.46 (*m*, 1 H), 1.55–1.75 (*m*, 2 H) and 1.80–1.94 (*m*, 1 H, 2 H–C(3′), 2 H–C(4′)); 2.17 (*d*, $J = 1.1$, 3 H–C(5)); 2.23 (*s*, 3 H–C(1)); 4.87, 4.94 (2*m*, $w_{1/2} = 4$, CH_2=C(6′)); 6.65 (*m*, $w_{1/2} = 4$, H–C(4)). ^{13}C-NMR: 20.5, 25.0, 25.5, 32.5 (4*q*, 4 CH_3); 21.5, 32.3, 37.8 (3*t*, C(3′), C(4′), C(5′)); 39.2, (*s*, C(2′)); 82.9 (*s*, C(1′)); 112.3 (*t*, CH_2=C(6′)); 125.6 (*d*, C(3)); 149.0, 158.8 (2*s*, C(4), C(6′)); 199.2 (*s*, C(2)). MS: 222 (3, M^+, $C_{14}H_{22}O_2$), 207 (7), 179 (52), 153 (19), 151 (24), 139 (29), 123 (24), 111 (46), 109 (28), 95 (18), 69 (31), 55 (17), *43* (100), 41 (30). Anal. calc. for $C_{14}H_{22}O_2$ (222.33): C 75.63, H 9.97; found: C 75.65, H 9.78.

2.3. *Hydrolysis of* **13**. A soln. of **13** (19 mg, 0.08 mmol) and oxalic acid (3.2 mg, 0.04 mmol) in dioxane (1 ml) and H_2O (0.5 ml) was stirred at 60° for 15 h. Workup in Et_2O and CC (pentane/hexane/Et_2O 1:1:1) afforded **21** [14] (9 mg, 47%).

2.4. *Hydratization of* **14**. A soln. of **14** (69 mg, 0.29 mmol) and oxalic acid (36 mg, 0.40 mmol) in THF (2 ml) and H_2O (1 ml) was stirred at r.t. overnight. Workup in Et_2O and CC (hexane/Et_2O 1:3) afforded **22** (27 mg, 37%).

(1RS,3RS,5RS,8RS)-3,5,8,12,12-Pentamethyl-2,6,7-trioxatricyclo[6.4.0.0^{1,5}]dodecan-3-ol (**22**). M.p. 117–118° (pentane). IR: 3480*m*, 2980*s*, 2930*s*, 2865*m*, 1680*w*, 1458*s*, 1440*s*, 1428*s*, 1412*s*, 1375*s*, 1362*s*, 1332*m*, 1309*m*, 1275*w*, 1240*s*, 1198*m*, 1160*s*, 1115*m*, 1062*s*, 1043*m*, 1028*s*, 978*m*, 961*m*, 943*m*, 928*m*, 915*s*, 896*s*, 878*w*, 865*w*, 830*w*. ^{1}H-NMR (300 MHz): 1.02, 1.06 (2*s*, 2 CH_3–C(12)); 1.34, 1.50, 1.63 (3*s*, CH_3–C(3)); CH_3–C(5), CH_3–C(8)); 1.30–1.40, 1.55–1.85, 1.95–2.10 (3*m*, 2 H–C(9), 2 H–C(10), 2 H–C(11)); 2.20 (*AB*, $J = 14$, $\delta_A = 2.04$, $\delta_B = 2.36$, 2 H–C(4)); 4.90 (*m*, $w_{1/2} = 4$, OH). ^{13}C-NMR (*ca.* 90% pure): 17.9, 21.8, 25.3, 25.5, 26.1 (5*q*, 5 CH_3); 18.7, 32.4, 36.2 (3*t*, C(9), C(10), C(11)); 38.1 (*s*, C(12)); 54.0 (*t*, C(4)); 88.7, 95.8, 101.4, 102.4 (4*s*, C(1), C(3), C(5), C(8)). MS: 238 (3, $M^+ - H_2O$), 195 (4), 191 (6), 110 (12), 100 (13), 95 (16), 85 (24), 71 (33), 69 (19), 58 (15), 55 (14), *43* (100), 41 (24).

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