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ONE-POT SYNTHESIS OF MACROCYCLIC DI- AND TETRA-LACTONES USING [2+2] PHOTOCYCLOADDITION REACTIONS OF DI-2-PYRONES WITH α,ω-DIOLEFINS

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Abstract – Sensitized photocycloaddition reactions of 6,6'-dimethyl-4,4'-[1,4-bis(methylenoxy)phenylene]-di-pyrone (**1**) with poly(ethyleneglycol)divinyl ethers (**2a**, **b**) or 2,2'-dimethyltrimethylene dimethacrylate (**4**), together with the reactions of 6,6'-dimethyl-4,4'-polymethylenedioxy-2-pyrones (**6a**, **b**) with **4** were described. The reactions of **1** with **2a**, **b** gave crown ether type macrocyclic compounds (**3a** and **3a'** (isomer of **3a**), **3b** and **3b'** (isomer of **3b**)) possessing 19- and 22-membered rings across the C3−C4 and C3'−C4' double bonds in **1**, respectively. Similar reactions of **1** with **4** and **6a**, **b** with **4** afforded different types of macrocycles (**5** and **5'**, **7a**, **b** and **7a'**, **b'**) having 19- to 21-membered rings across the C5−C6 and C5'−C6' double bonds in 2-pyrone ring. The stereochemical features of **3a'** and **5** were determined by X-ray crystal analysis. The reaction mechanism was inferred by MO methods.

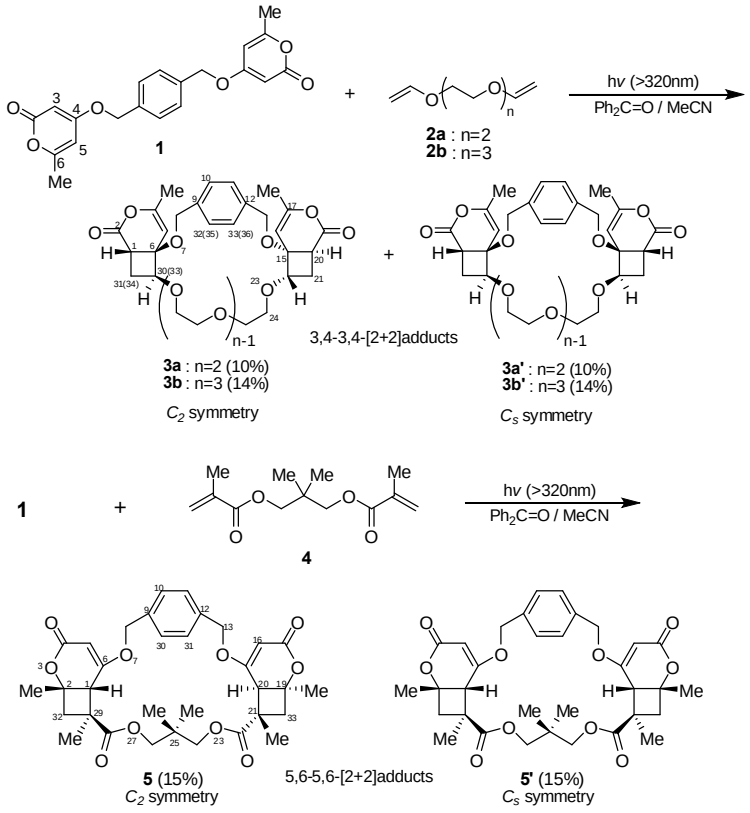
INTRODUCTION

The synthesis of macrocyclic ring systems is an important area in organic chemistry. There are several strategies to prepare macrocyclic compounds, including cyclization, capping and condensation using thermal reactions.[1] Photochemical reactions are also an effective approach.[2] Although the [2+2] cycloaddition reaction is a useful method in the synthesis of a variety of macrocycles with one or two cyclobutane rings,[3] little attention has been paid to the synthesis of macrocyclic compounds from the sequential inter- and intramolecular [2+2] photocycloaddition reactions between substrates possessing two enones and α, ω-diolefins, because of the predicted complications with several reactions. We have recently succeeded in accomplishing a one-pot synthesis of macrocyclic compounds from the sequential inter- and intramolecular [2+2] photocycloadditions of di-2-pyrones with α,ω-diolefins,[4] together with an

MO analysis that the origin of a remarkable change in regioselectivities of the inter- and intramolecular photocycloadditions.[5] We planned to extend the one-pot synthesis of macrocyclic compounds to di-2-pyrone tethered by the *p*- position of the benzene ring (**1**) and polymethylenedioxy-di-2-pyrones (**6a**, **b**) to investigate the generality of the sequential inter- and intramolecular photoreactions with electron-rich and electron-poor α,ω-diolefins (**2a**, **b** and **4**) .

RESULTS AND DISCUSSION

p-Di-2-pyrone (**1**) was prepared from dehydrochlorination of 4-hydroxy-6-methyl-2-pyrone with 1,4-bis(chloromethyl)benzene using 1,8-diazabicyclo[5.4.0]-7-undecene in 30% yield. Polymethylene-dioxy-di-2-pyrones (**6a**, **b**) were prepared according to the method previously described in the literature.[6] A solution of **1** (20 mM) with two equivalents of di(ethyleneglycol)divinyl ether (**2a**) in acetonitrile was irradiated in the presence of benzophenone as a sensitizer with a 300 W high-pressure mercury lamp using a UV cutoff filter under 320 nm and under a nitrogen atmosphere. The reaction was followed by TLC and 24 h irradiation was required to fully convert the entire starting compound **1**. An amount of two equivalents of **2a** was required because of the polymerization of **2a** by irradiation. After removal of the solvent, the oily residue was chromotographed by silica gel (eluent: ethyl acetate/hexane = 2:1, v/v) to afford a mixture of **3a** and **3a'** (1:1) (3,4-3,4-[2+2] cycloadducts) in 20% yield, which were the major products from ^{1}H NMR spectra of the reaction mixture, together with a complex mixture that we were unable to isolate (Scheme 1).



Scheme 1

The isomers of **3a** and **3a'**, having C_2 symmetry and *Cs* symmetry, respectively, were separated by recrystallization from acetonitrile/chloroform (2:1, v/v). The structure of **3a'** was confirmed as the regioselective [2+2] cycloadduct, 4,17-dimethyl-3,7,14,18,23,26,29-heptaoxahexacyclo-[29.2^{9,12}.0.0^{1,6}.0^{6,30}.0^{15,20}.0^{15,22}]tritriaconta-4,9,11,16,32-pentaen-2,19-dione (22-*exo*, 30-*exo* adduct), across the C3-C4 and C3'-C4' double bonds in **1** with two olefin parts in **2a** by X-ray crystallographic analysis (Figure 1). The ORTEP drawing of **3a'** shows a 19-membered ring structure with two cyclobutane rings. Another product **3a** was estimated as the facial selective isomer at the C3−C4 and C3'-C4' double bonds in **1** with **2a** because this compound gave similar ^{1}H NMR spectral data as acquired for **3a'**. The stereochemistry of **3a'** in each cyclobutane ring was the *exo* conformation between 3,4-dihydropyrone ring and the alkoxy group, as determined from the X-ray structural analysis. The result of the similar photoreaction of **1** with **2b** is summarized in Table 1. The stereochemistry of each product (**3b**, **3b'**) was estimated to be C_2 symmetry and *C*s symmetry, respectively, from the comparison of the ^{1}H NMR data with those of **3a** and **3a'**.

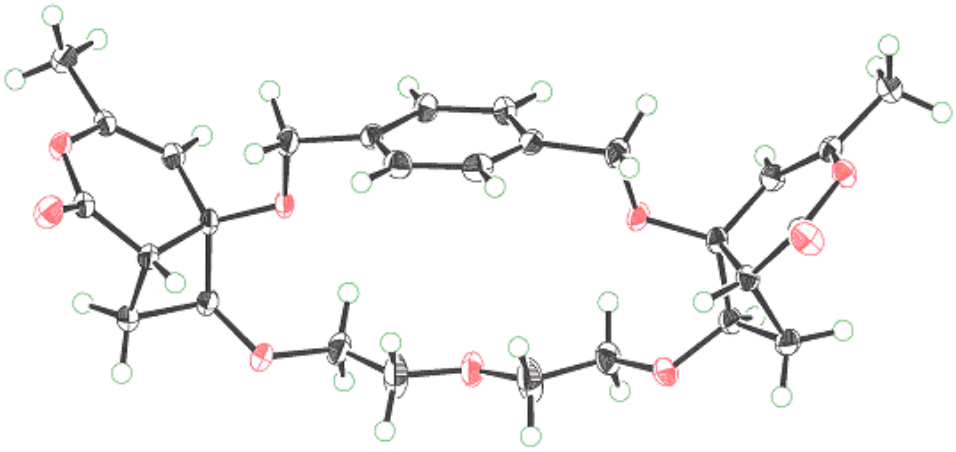


Figure 1. ORTEP drawing of **3a'**

Table 1. Photoreaction of di-2-pyrones (**1, 6a, b**) with electron-rich (**2a, b**) or electron-poor diolefins (**4**)

Di-2-pyrones	Diolefins	Irradiation time (h)	Conversion of **1, 6a, b** (%)	Product (yield, %)	
				3,4-3,4-[2+2] Adducts	5,6-5,6-[2+2] Adducts
1	**2a**	24	90[a]	**3a**(10), **3a'**(10)[a]	-
1	**2b**	26	99[a]	**3b**(14), **3b'**(14)[a]	-
1	**4**	20	100[b]	-	**5**(15), **5'**(15)[b]
6a	**4**	18	77[b]	-	**7a**(11.5),**7a'**(11.5)[b]
6b	**4**	18	75[b]	-	**7b**(12.5),**7b'**(12.5)[b]

[a] Estimated from NMR spectral analyses using internal standard (benzophenone).
[b] Estimated from NMR spectral analyses using internal standard (fumaronitrile).

Photoreaction of **1** with 2, 2'-dimethyltrimethylene dimethacrylate (**4**) was also carried out in the same reaction conditions mentioned above. After removal of the solvent, the oily residue was chromatographed by silica gel (eluent: ethyl acetate/hexane = 2:1, v/v) to afford a 1:1 mixture of **5** and **5'** (*exo*-*exo* 5,6-5,6-[2+2] cycloadducts) in 30% yield. Compounds **5** and **5'** were separated by fractional recrystallization from acetonitrile. The structure of **5** was confirmed as the regioselective [2+2] cycloadduct, 2,19,21,25,25,29-hexamethyl-3,7,14,18,23,27-hexaoxahexacyclo[27.2^{30,31}.1^{2,29}.1^{19,21}.0.0^{1,6}.0^{15,20}]nonacosa-5,9,11,15,30-pentaen-4,17,22,28-tetraone (21-*exo*, 29-*exo* adduct, C_2 symmetry), across the C5−C6 and C5'−C6'-double bonds in **1** with two olefin parts in **4** by X-ray crystallographic analysis (Figure 2).

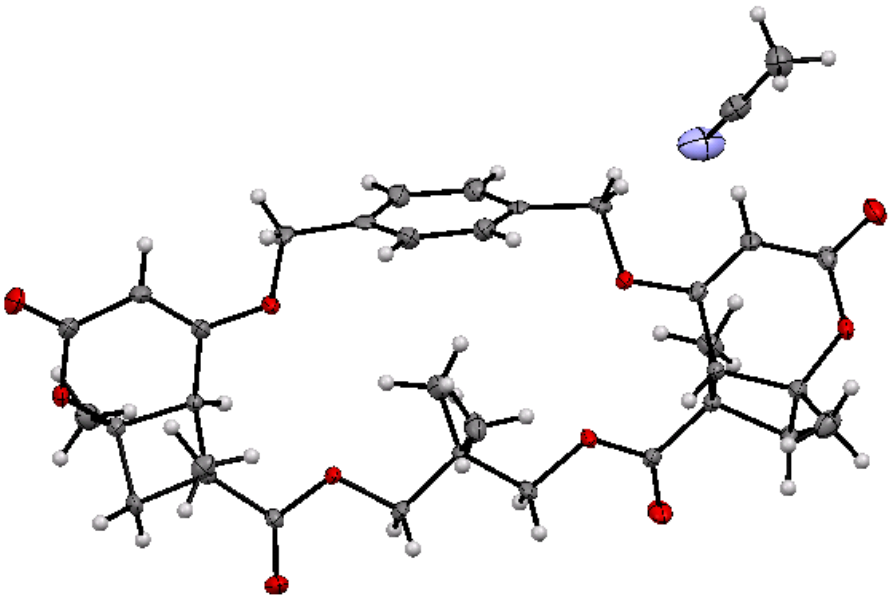
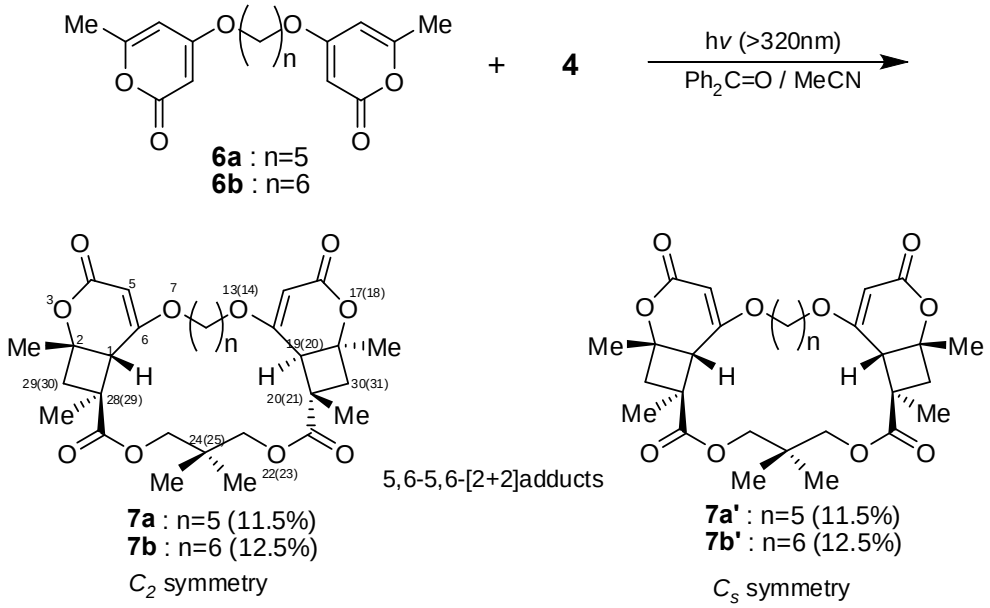


Figure 2. ORTEP drawing of **5**

The ORTEP drawing of **5** shows the 21-membered ring structure. Another product **5'** was estimated as the facial selective isomer (*C*s symmetry) at the C5−C6 and C5'−C6' double bonds in **1** with **4** because these compounds showed similar spectral properties to the NMR data of **5**. The chemical shifts of the methyl groups at the 25-position of **5** and **5'** showed δ 0.44 (**5**), δ 0.26 and 0.52 (**5'**), respectively, owing to the shielding effect of the benzene ring in **5** and **5'**. Photoreaction of **6a** (n=5) with **4** was also carried out in the same reaction conditions mentioned above. After removal of the solvent, the oily residue was chromatographed by silica gel (eluent: ethyl acetate/hexane = 3:1, v/v) to afford a 1:1 mixture of **7a** and **7a'** (*exo*-*exo* 5,6-5,6-[2+2] cycloadducts) in 23% yield (Scheme 2). Product **7a** was isolated by recrystallization from acetonitrile, but unfortunately it was hard to obtain as a single crystal. The structure of **7a** was estimated as the regioselective [2+2] cycloadduct, 2,18,20,24,24,28-hexamethyl-3,7,13,17,22,

26-hexaoxapenta-cyclo[26.1^{2,28}.1^{18,20}.0.0^{1,6}.0^{14,19}]octacosa-5,14-dien-4,16,21,27-tetraone (20-*exo*, 27-*exo* adduct, C_2 symmetry) from the comparison of the ^{1}H-NMR spectral data with **5** and **5'**. Another product **7a'** was estimated as the facial selective isomer (*C*s symmetry). The result of the similar photoreaction of **6b** (n=6) with **4** is summarized in Table 1. Unfortunately a mixture of [2+2] cycloadducts **7b** and **7b'** were difficult to isolate despite many crystallization trials. Since the yields of the macrocyclic compounds **3**, **5**, **7** were relatively low (20−30%), we considered the formation of the other stereoisomers of the macrocycles possessing two cyclobutane rings, oxetanes between di-2-pyrones and benzophenone (sensitizer),[7] and inter- or intramolecular [2+2] photocycloadducts of di-2-pyrones[6] in this system.



Scheme 2

We next describe the photocycloaddition mechanism using the PM5 level.[8] Figure 3 shows energies and coefficients of the higher singly occupied molecular orbital (HSOMO) and lower ones (LSOMO) of the triplet states by means of the PM5 level, and those of the LUMO and HOMO of the ground states of two α,ω-diolefins, **2** and **4**, by means of the PM5 level. Since these photoadditions were sensitized by a triplet sensitizer (benzophenone), they were inferred to proceed via a two-step radical path, and that the first steps were mainly influenced by the energies and coefficients of the two frontier orbitals, respectively. The reasonable processes via radical intermediates (I and II in Figure 4) are inferred from the narrow gap (Δε) of the energies and the large coefficients (C_i and C_r) between two substrates are quantitatively confirmed by the large two-center frontier orbital interactions in Table 2.

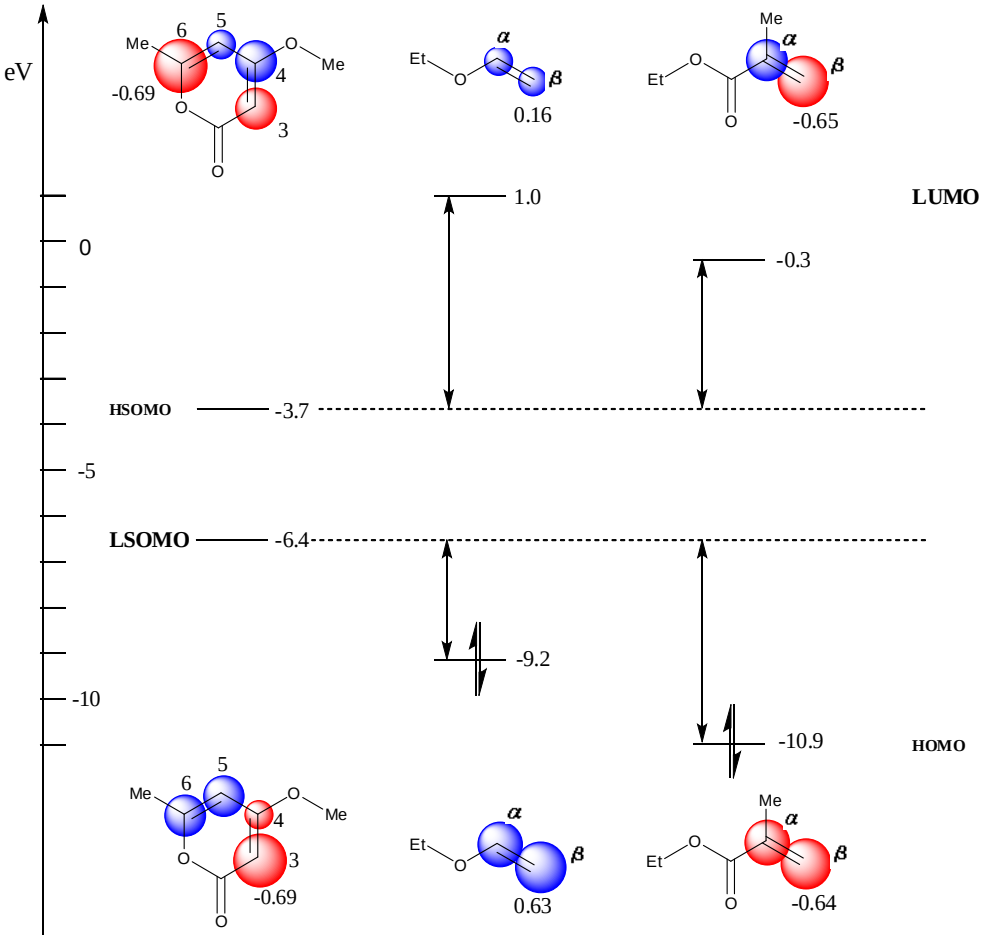


Figure 3. Estimated energies and coefficients of triplet 2-pyrones and ground state olefins by means of PM5 level[5]

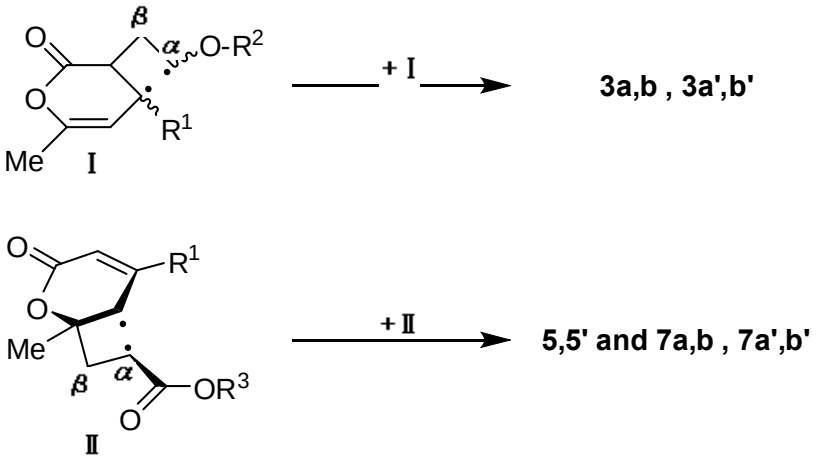


Figure 4. Two types of intermediate structures

Table 2. Estimated frontier orbital interactions between 2-pyrones and olefins by the PM5 calculation (γ^2/eV)

	2		4	
Position	C3 -Cβ [a]	C6 - Cβ [b]	C3 -Cβ	C6 - Cβ
2-pyrone Δε	2.8	4.7	4.5	3.4
$(C_iC_r)^2/\Delta\varepsilon$	0.067	0.003	0.043	0.059

[a] Left : LSOMO (2-pyrone) - HOMO (2 or 4) interaction.
[b] Right: HSOMO (2-pyrone) - LUMO (2 or 4) interaction.

Interactions, $(CiCr)^2/\Delta\varepsilon$ (in γ^2/eV), have a tendency to be larger between C3 (2-pyrone) and Cβ (olefin **2**), or C6 (2-pyrone) and Cβ (olefin **4**) than others. In the concrete, with **2** having an electron-donating group, the C3-Cβ interactions between the LSOMO and HOMO are larger than others, and with **4** having an electron-withdrawing group, the C6-Cβ interactions between the HSOMO and LUMO are relatively large. The photoreactions of **1** with **2**, and **1** or **6** with **4** are strongly supported to go through the respective intermediates (**I** and **II**) in Figure 4. In summary, sensitized photocycloaddition reactions of *p*-di-2-pyrone (**1**) with electron-rich α,ω-diolefins (**2a**, **b**) gave crown ether-type macrocyclic compounds (**3a**, **b**) across the C3-C4 and C3'-C4' double bonds in **1** with two olefin parts in **2a**, **b**, having 19- and 22-memered rings. On the other hand, similar photoreactions of **1** or polymethylene dioxy-di-2-pyrones (**6a**, **b**) with electron-poor α,ω-diolefin (**4**) afforded macrocyclic dioxatetralactones (**5** and **7**) across the C5-C6 and C5'-C6' double bonds in **1** or **6** with two olefin parts in **4** having 19- to 21-membered rings. A sequential inter- and intramolecular [2+2] photocycloaddition mechanism in this system was reasonably interpreted by an MO analysis.

EXPERIMENTAL

All melting points were measured on Yanagimoto Melt-tem apparatus and uncorrected. NMR spectra were measured at 400MHz on the JNM GSX-400 (TMS as an internal standard). IR spectra were recorded with a JASCO IR Report-100spectrometer. Mass spectra were recorded with a JEOL JMS-HX110A (FABMS) using *m*-nitrobenzyl alcohol as matrix. Elemental analysis was made using a Yanaco MT-5. Single crystal X-ray diffraction analyses of **3a'**, **5**, and **7a** were performed on a Rigaku RAXIS-RAPID imaging plate diffractometer with graphite monochromated Mo Kα radiation. Lorentz and polarization corrections were applied to the intensity data. The structures were solved by direct methods using SHELX-97[9] or SIR 92[10] and refined by a full-matrix least-squares method. The non-hydrogen atoms were refined anisotopically. All calculations were performed using the teXsan[11] crystallographic soft ware package. Photoirradiations were carried out in the Pyrex tube using 300 W high-pressure mercury lamp. Wakogel C200 was used for preparative column chromatography.

6,6'-Dimethyl-4,4'-[1,4-bis(methylenoxy)phenylene]-di-2-pyrone (**1**) ….. To a refluxing MeCN (200 mL) solution of 4-hydroxy-6-methyl-2-pyrone (20.0 g, 160 mmol) and DBU (26.2 g, 170 mmol) was slowly added 1,4-bis(chloromethyl)benzene 14.0 g, 80 mmol) and refluxing was continued for 72 h. After cooling to room temperature, the reaction mixture was evaporated in vacuo and the resulting oily residue was dissolved in $CHCl_3$ (200 mL). To the concentrate was added acetic acid and water, and the mixture was stirred for 1 h at room temperature. The mixture was washed with brine, dried with anhydrous magnesium sulfate, and filtered. The filtrate was concentrated to dryness under reduced pressure, and the residue was recrystallized from MeCN to give **1** (8.21 g, 30%).

1: mp 210−212 ºC. ^{1}H NMR ($CDCl_3$) δ 2.22 (6H, s, Me), 5.03 (4H, s, CH_2), 5.48, 5.85 (each 2H, d, J = 1.6 Hz, CH), 7.41 (4H, s, Ar-H). IR (KBr) 1710, 1640 cm^{-1}. LR MS m/z 355 (MH^+). *Anal*. Calcd for $C_{20}H_{18}O_6$: C, 67.79, H, 5.12. Found: C, 67.66, H, 5.16).

4,17-Dimethyl-3,7,14,18,23,26,29-heptaoxahexacyclo[29.2^{9,12}.0.0^{1,6}.0^{6,30}.0^{15,20}.0^{15,22}]tritriaconta-4,9,11,16,32-pentaen-2,19-dione (22-*exo*, 30-*exo* adduct) (3a) (*C*$_2$ symmetry) and (3a') (*C*s symmetry) ….. To a solution of **1** (1.42 g, 4.00 mmol) with di(ethyleneglycol)divinyl ether **(2a**) (1.22 g, 8.02 mmol) in MeCN (200 mL) was irradiated in the presence of benzophenone (0.327 g, 1.80 mmol) for 24 h. After removal of the solvent, the oily residue was chromatographed by silica gel (eluent: EtOAc/hexane = 2:1, v/v) to give a mixture of **3a** and **3a'** (1:1) (369 mg, 20% yield). Compound **3a'** was separated by recrystallization from a mixture of MeCN and $CHCl_3$ (2:1).

3a: oil. ^{1}H NMR ($CDCl_3$) δ 2.04 (2H, m, CH_2), 2.05 (6H, s, Me), 2.16 (2H, t, J =12.8 Hz, CH_2), 3.28-3.40 (2H, m, CH_2), 3.48 (2H, t, J = 9.6Hz, CH), 3.59-3.73 (2H, m, CH_2), 3.70 (2H, d, J = 5.2 Hz, CH), 4.19 (2H, d, J = 10.8 Hz, CH_2), 4.47 (2H, d, J = 10.8 Hz, CH_2), 5.06 (2H, s, CH), 7.32 (4H, Ar-H). IR (neat) 1760, 1685 cm^{-1}. LR MS m/z 513 (MH^+). HR MS (MH^+) calcd for $C_{28}H_{33}O_9$ 513.2125. found: 513.2094.

3a': mp 231−233 ºC. ^{1}H NMR ($CDCl_3$) δ 2.04 (6H, s, Me), 2.09 (2H, ddd, J = 12.4, 9.6, 5.6 Hz, CH_2), 2.19 (2H, dd, J = 12.4, 9.6 Hz, CH_2), 3.17 (2H, ddd, J = 13.2, 7.6, 5.2 Hz, CH_2), 3.28 (2H, ddd, J = 13.2, 7.6, 6.0 Hz, CH_2), 3.39 (2H, dt, J = 7.6, 5.2 Hz, CH_2), 3.45 (2H, dt, J = 7.6, 6.0 Hz, CH_2), 3.59 (2H, t, J = 9.6 Hz, CH), 3.77 (2H, d, J = 5.6 Hz, CH), 4.15 (2H, d, J = 10.0 Hz, CH_2), 4.36 (2H, d, J = 10.0 Hz, CH_2), 4.95 (2H, s, CH), 7.33 (4H,s, Ar-H). IR (KBr) 1760, 1695 cm^{-1}. LR MS m/z 513 (MH^+). *Anal*. Calcd for $C_{28}H_{32}O_9$: C, 65.61, H, 6.29. Found: C, 65.59, H, 6.15.

X-Ray crystal data for **3a'** ($C_{28}H_{32}O_9$): M = 512.54, crystal dimensions 0.54x0.42x0.38 mm^3, orthorhombic, space group *Pnma*, a = 8.32670(10) Å, b = 31.8091(4) Å, c = 10.0349(2) Å, α = 90 º, β = 90 º, γ = 90 º, V = 2657.89(7) Å^3, Z = 4, ρ_{calc} = 1.281 mg/m^3, $2\theta_{max}$ = 55.0 º, T = 113(2) K, R = 0.0417, R_w = 0.1190, GOF = 1.162.

4,17-Dimethyl-3,7,14,18,23,26,29,32-octaoxahexacyclo[32.2^{9,12}.0.0^{1,6}.0^{6,33}.0^{15,20}.0^{15,22}]hexatriaconta-4,9,11,16,35-pentaen-2,19-dione (22-*exo*, 33-*exo* adduct) (3b) (*C*$_2$ symmetry) and (3b') (*C*s symmetry) ….. To a solution of **1** (0.708 g, 2.00 mmol) with tri(ethyleneglycol)divinyl ether **(2b**) (0.724

g, 3.58 mmol) in MeCN (200 mL) was irradiated in the presence of benzophenone (0.364 g, 2.00 mmol) for 7 h. After removal of the solvent, the oily residue was chromatographed by silica gel (eluent: EtOAc/hexane = 2:1, v/v) to give a mixture of **3b** and **3b'** (1:1) (308 mg, 28% yield). Compounds **3b** and **3b'** were separated by recrystallized from a mixture of MeCN and $CHCl_3$ (2:1).

3b: mp 196−199 ºC. ^{1}H NMR ($CDCl_3$) δ 2.04 (6H, s, Me), 2.16 (2H, ddd, *J* = 12.8, 10.4, 5.6 Hz, CH_2), 2.31 (2H, t, *J* = 12.8 Hz, CH_2), 3.40-3.62 (8H, m, CH_2), 3.56 (2H, dd, *J* = 12.8, 10.4 Hz, CH), 3.74 (2H, m, CH_2), 3.88 (2H, d, *J* = 5.6 Hz, CH), 3.99 (2H, m, CH_2), 4.12 (2H, d, *J* = 11.2 Hz, CH_2), 4.42 (2H, d, *J* = 11.2 Hz, CH_2), 4.98 (2H, s, CH), 7.33 (4H,s, Ar-H). IR (KBr) 1763, 1689 cm^{-1}. LR MS m/z 557 (MH^+). HR MS (MH^+) calcd for $C_{30}H_{37}O_{10}$ 557.2387. found: 557.2354. *Anal*. Calcd for $C_{30}H_{36}O_{10}$: C, 64.74, H, 6.52. Found: C, 64.56, H, 6.57.

3b': mp 222−226 º. ^{1}H NMR ($CDCl_3$) δ 2.04 (6H, s, Me), 2.17 (2H, ddd, *J* = 12.8, 10.4, 5.6 Hz, CH_2), 2.31 (2H, t, *J* = 12.8 Hz, CH_2), 3.40-3.63 (8H, m, CH_2), 3.59 (2H, dd, *J* = 12.8, 10.4 Hz, CH), 3.74 (2H, m, CH_2), 3.89 (2H, d, *J* = 5.6 Hz, CH), 3.99 (2H, m, CH_2), 4.19 (2H, d, *J* = 11.2 Hz, CH_2), 4.37 (2H, d, *J* = 11.2 Hz, CH_2), 4.94 (2H, s, CH), 7.35 (4H,s, Ar-H). IR (KBr) 1757, 1684 cm^{-1}. LR MS m/z 557 (MH^+). HR MS (MH^+) calcd for $C_{30}H_{37}O_{10}$ 557.2387. found: 557.2390. *Anal*. Calcd for $C_{30}H_{36}O_{10}$: C, 64.74, H, 6.52. Found: C, 64.24, H, 6.62.

2,19,21,25,25,29-Hexamethyl-3,7,14,18,23,27-hexaoxahexacyclo[27.2^{30,31}.1^{2,29}.1^{19,21}.0.0^{1,6}.0^{15,20}]nonacosa-5,9,11,15,30-pentaen-4,17,22,28-tetraone (21-*exo*, 29-*exo* adduct) (5) *C*$_2$ symmetry) and (5') (*C*s symmetry) ….. To a solution of **1** (0.893 g, 2.52 mmol) with 2,2'-dimethyltrimethylene dimethacrylate **(4)** (1.01 g, 4.21 mmol) in MeCN (200 mL) was irradiated in the presence of benzophenone (0.204 g, 1.12 mmol) for 18 h. After removal of the solvent, the oily residue was chromatographed by silica gel (eluent: EtOAc/hexane = 2:1, v/v) to give a mixture of **5** and **5'** (1:1) (449 mg, 30% yield). A mixture of compounds **5** and **5'** was separated by recrystallized from a mixture of MeCN and $CHCl_3$ (1:1).

5: mp 251−254 ºC. ^{1}H NMR ($CDCl_3$) δ 0.44, 1.37, 1.53 (each 6H, s, Me), 2.25 (2H, d, *J* = 13.2 Hz, CH_2), 2.83 (2H, d, *J* = 13.2 Hz, CH_2), 3.18 (2H, s, CH), 3.57, 3.75 (each 2H, d, *J* = 10.8 Hz), 4.84, 4.93 (each 2H, d, *J* = 10.4 Hz), 5.49 (2H, s, CH). IR (KBr) 1730, 1703, 1628 cm^{-1}. LR MS m/z 595 (MH^+), *Anal*. Calcd for $C_{33}H_{38}O_{10}\cdot CH_3CN$: C, 65.79, H, 6.53, N, 1.99. Found: C, 66.10, H, 6.51, N, 2.20.

X-Ray crystal data for **5** ($C_{33}H_{38}O_{10}\cdot CH_3CN$) : *M* = 635.70, crystal dimensions 0.20 x 0.10 x 0.10 mm^3, monoclinic, space group *C2/c* (#15), *a* = 33.161(10) Å, *b* = 9.219(3) Å, *c* = 11.998(4) Å, *β* = 108.6990 (19) º, V = 3474.5(18) Å^3, Z = 5, ρ_{calc} = 1.454 g/cm^3, $2\theta_{max}$ = 55.0 º, T = 123 K, R = 0.0817, R_w = 0.2257, GOF = 1.057.

5': oil. ^{1}H NMR ($CDCl_3$) δ 0.26 , 0.52 (each 3H, s, Me), 1.41, 1.53 (each 6H, s, Me), 2.26, 2.83 (each 2H, d, *J* = 13.6 Hz, CH_2), 3.16 (2H, s, CH), 3.54, 3.76 (each 2H, d, *J* = 10.8 Hz, CH_2), 4.84, 4.89 (each 2H, d, *J* = 9.6 Hz, CH_2), 5.50 (2H, s, CH), 7.42 (4H, s, Ar-H). IR (KBr) 1720, 1703, 1622 cm^{-1}. LR MS m/z 595 (MH^+). HR MS (MH^+) calcd for $C_{33}H_{39}O_{10}$ 595.2543. found: 595.2520.

2,18,20,24,24,28-Hexamethyl-3,7,13,17,22,26-hexaoxapentacyclo[26.1^{2,28}.1^{18,20}.0.0^{1,6}.0^{14,19}]octacosa-5,14-dien-4,16,21,27-tetraone (20-*exo*, 27-*exo* adduct) (7a) (*C*$_2$ symmetry) and (7a') (*C*s symmetry) **…..** To a solution of **6a** (0.640 g, 2.00 mmol) with **4** (0.724 g, 3.00 mmol) in MeCN (100 mL) was irradiated in the presence of benzophenone (0.182 g, 1.00 mmol) for 10 h. After removal of the solvent, the oily residue was chromatographed by silica gel (eluent: EtOAc/hexane = 1:1, v/v) to give a mixture of **7a** and **7a'** (1:1) (198 mg, 23% yield). Compound **7a** was separated by fractional recrystallization from MeCN.

7a: mp 272−274 ºC. ^{1}H NMR ($CDCl_3$) δ 1.01 (2H, m, CH_2), 1.04, 1.33, 1.52 (each 6H, s, Me), 1.76 (4H, m, CH_2), 2.32 (2H, d, *J* = 13.2 Hz, CH_2), 2.64 (2H, dd, *J* = 13.2, 1.2 Hz, CH_2), 3.45 (2H, s, CH), 3.80 (2H, d, *J* = 11.2 Hz, CH_2), 3.92 (4H, m, CH_2), 4.14 (2H, d, *J* = 11.2 Hz, CH_2), 5.28 (2H, s, CH). IR (KBr) 1731, 1705, 1627 cm^{-1}. LR MS m/z 561 (MH^+). HR MS (MH^+) calcd for $C_{30}H_{41}O_{10}$ 561.2700. found: 561.2690. *Anal*. Calcd for $C_{30}H_{40}O_{10}$: C, 64.23, H, 7.14. Found: C, 64.51, H, 6.95.

7a': mixture with **7a**. ^{1}H NMR ($CDCl_3$) δ 1.01 (2H, m, CH_2), 1.04, 1.32, 1.54 (each 6H, s, Me), 1.76 (4H, m, CH_2), 2.29 (2H, d, *J* = 13.2 Hz, CH_2), 2.74 (2H, dd, *J* = 13.2, 1.2 Hz, CH_2), 3.37 (2H, s, CH), 3.90 (2H, d, *J* = 10.8 Hz, CH_2), 3.95 (4H, m, CH_2), 4.06 (2H, d, *J* = 10.8 Hz, CH_2), 5.28 (2H, s, CH).

2,19,21,25,25,29-Hexamethyl-3,7,14,18,23,27-hexaoxapentacyclo[27.1^{2,29}.1^{19,21}.0.0^{1,6}.0^{15,20}]nonacosa-5,15-dien-4,17,22,28-tetraone (21-*exo*, 28-*exo* adduct) (7b) (*C*$_2$ symmetry) and (7b') (*C*s symmetry) **…..** To a solution of **6b** (0.670 g, 2.00 mmol) with **4** (0.723 g, 3.00 mmol) in MeCN (100 mL) was irradiated in the presence of benzophenone (0.180 g, 1.00 mmol) for 24 h. After removal of the solvent, the oily residue was chromatographed by silica gel (eluent: EtOAc/hexane = 1:1, v/v) to give a mixture of **7b** and **7b'** (1:1) (215 mg, 25% yield), whose compounds were difficult to separate each other by recrystallization.

7b and **7b'** (1:1 mixture): ^{1}H NMR ($CDCl_3$) δ 1.00 (4H, m, CH_2), 1.04, 1.36, 1.53 (each 6H, s, Me), 1.73 (4H, m, CH_2), 2.27 (2H, d, *J* = 13.2 Hz, CH_2), 2.78 (2H, d, *J* = 13.2 Hz, CH_2), 2.80 (2H, d, *J* = 13.2 Hz, CH_2), 3.30 (2H, s, CH), 3.90 (4H, m, CH_2), 4.05, 4.07 (4H, d, *J* = 11.2 Hz, CH_2), 5.29 (2H, s, CH). IR (KBr) 1713, 1631 cm^{-1}. LR MS m/z 575 (MH^+). HR MS (MH^+) calcd for $C_{31}H_{43}O_{10}$ 575.2856. found: 575.2845.

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REFERENCES

1. B. Dietrich, P. Viout, and J.-M. Lehn, *Macrocyclic Chemistryt*, VCH:Weinheim, 1993.
2. A. G. Griesbeck, A. Henz, and J. Hirt, *Synthesis*, 1996, 1261.

3. J. Nishimura, H. Doi, A. Ohbayasi, and A. Oku, *J. Am. Chem. Soc*., 1987, **109**, 5293; S. Inokuma, M. Takezawa, H. Satoh, Y. Nakamura, T. Sasaki, and J. Nishimura, *J. Org. Chem*., 1998, **63**, 5791; S. Inokuma, T. Ide, T. Yonekura, T. Funaki, S. Kondo, S. Shinobara, T. Yoshihara, S. Tobita, and J. Nishimura, *J. Org. Chem*., 2005, **70**, 1698.
4. T. Shimo, M. Kawamura, E. Fukushima, M. Yasutake, T. Shinmyozu, and K. Somekawa, *Heterocycles*, 2003, **60**, 23.
5. H. Miyauchi, C. Ikematsu, T. Shimazaki, S. Kato, T. Shinmyozu, T. Shimo, and K. Somekawa, *Tetrahedron*, 2008, **64**, 4108.
6. T. Shimo, S. Ueda, T. Suishu, and K. Somekawa, *J. Heterocycl. Chem*., 1995, **32**, 727.
7. W. Wang, T. Shimo, H. Hashimoto, and K. Somekawa, *Tetrahedron*, 2007, **63**, 12367.
8. Y. Odo, T. Shimo, K. Hori, and K. Somekawa, *Bull. Chem. Soc. Jpn.*, 2003, **60**, 23.
9. G. M. Sholdrick, *SHELX-97*, *Program for the Refinement of Crystal Structures*; University of Gottingen: Gottingen, Germany, 1997.
10. A. Altomare, M. C. Burla, M. Camalli, M. Cascarano, C. Giacovazzo, A. Guagliardi, and G. Polidori, *J. Appl. Crystallogr.,* 1994, **27**, 435.
11. *Crystal structure analyses package, mo*lecular structure corporation (1985 and 1999).