Synthesis of *endo,endo*-2.9-Dihydroxypentacyclo-[8.4.0.0^{3,8}.0^{4,14}.0^{7,11}]tetradeca-5,12-diene

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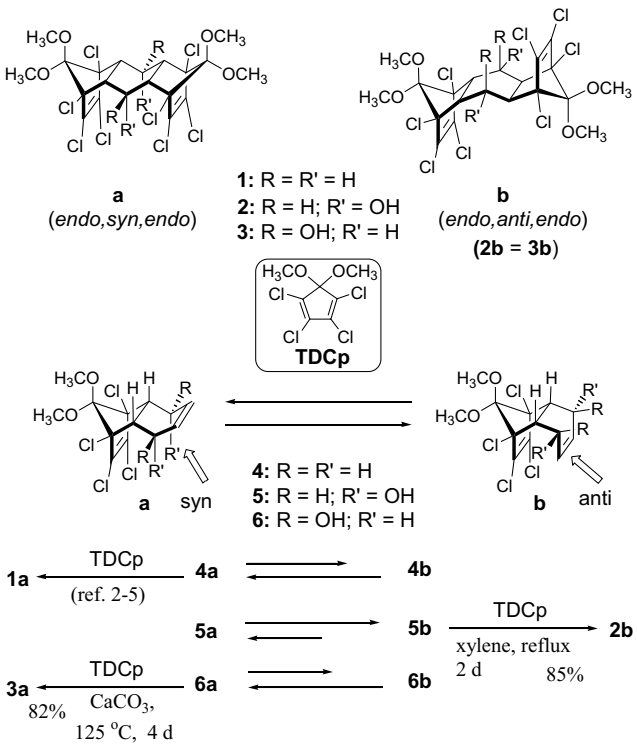
The title compound **30** was synthesized starting from the endo,syn,endo Diels-Alder adduct **3a** of hexahydro-5,6,7,8-tetrachloro-9,9-dimethoxy-5,8-methanonaphthalene-1,4-diol diacetate **6** and 1,2,3,4-tetrachloro-5,5-dimethoxycyclopentadiene (TDCp) in six steps, keyed upon a symmetry-allowed [4+4] photocyclization of decahydro-11,12-dioxo-[1,4;5,8]dimethanoanthracene-9,10-diol diacetate **22**. The epimeric monoacetate **26** related to **22** was also synthesized and their thermolysis and photolysis were investigated. Oxidation of diol **30** afforded hexacyclic bridged hemiacetal **31** as a result of transannular reaction. The structure of hemiacetal **31** was analyzed by single-crystal X-ray crystallography.

Keywords: 1,2,3,4-Tetrachloro-5,5-dimethoxycyclopentadiene; Diels-Alder reaction; Polycyclic compounds; Cage compounds.

INTRODUCTION

The Diels-Alder reaction of 1,2,3,4-tetrachloro-5,5-dimethoxycyclopentadiene (TDCp)[1] and 1,4-cyclohexadiene produced a 2:1 adduct **1a**.[2] Its endo,syn,endo stereostructure, rather than the endo,anti,endo **1b**, is evident from ^{1}H NMR spectrum[2b] and later confirmed by chemical transformations.[3-5] As illustrated in Scheme I, the initially formed 1:1 endo adduct **4** presumably adopts the sterically more favored "unfolded" boat-conformation (**4a**), which allows the cycloaddition to occur at the less sterically demanding π-face syn to the existing dichlorinated double bond, resulting in the formation of endo,syn,endo adduct **1a**.[2] However, this mode of π-facial selectivity was not observed in our attempt to synthesize *endo*,*syn*,*endo*-diol **2a** via the Diels-Alder reaction of TDCp with *endo*,*endo*-diol **5**[6] derived from $CeCl_3$-mediated $NaBH_4$ reduction of the Diels-Alder adduct of 1,4-benzoquinone and TDCp. The Diels-Alder reaction afforded instead the endo,anti,endo adduct **2b** as sole product in 85% yield.[7] Presumably, *endo*,*endo*-diol **5** preferably adopts the "folded" boat-conformation (**5b**), instead of the more sterically crowded "unfolded" boat-conformation (**5a**), in which the two face-to-face hydroxyl groups occupy the concave position and are in proximity to the dichlorinated double bond. Furthermore, both π-faces in conformation **5a** are sterically hindered due to the hydroxyl groups and ring-junction hydro-

Scheme I



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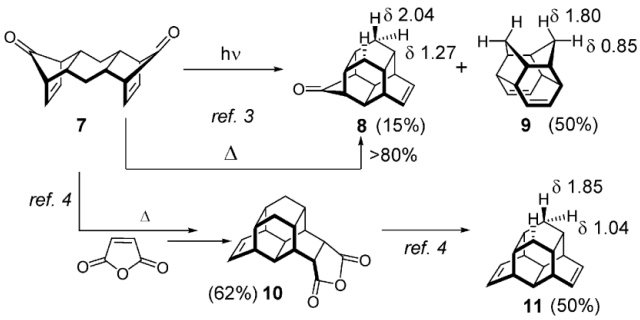
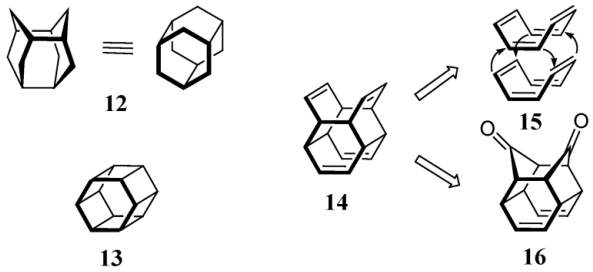
gens, and hence the Diels-Alder reaction of **5** occurs at the anti π-face (opposite to the dichlorinated double bond) of the conformation **5b** to yield *endo*,*anti*,*endo*-diol **2b**. It was believed that inverting the configuration of a carbon atom bearing a hydroxyl group could reverse the conformational preference[8] and hence the conformation-controlled π-facial selectivity in the Diels-Alder reaction. The resulting *exo*,*exo*-diol **6** would employ the more stable and sterically less demanding "unfolded" boat-conformation **6a** to undergo a syn cycloaddition with TDCp to furnish *endo*,*syn*,*endo*-diol **3a**, instead of the "folded" boat-conformation **6b**, where both π-faces are sterically more demanding due to the hydroxyl groups and the dichlorinated double bond. This speculation led us[7] and another[9] to successfully prepare *exo*,*exo*-diol **6** and Diels-Alder *endo*,*syn*,*endo*-diol adduct **3a** for use as starting materials in the synthesis of a variety of novel polycyclic systems.

Reductive dechlorination of **1a** followed by acid-catalyzed hydrolysis of ketal groups furnished pentacyclic dione **7**.[3,4] As shown in Scheme II, upon irradiation in a benzene solution, dione **7** was found[3] to undergo sequential decarbonylation with successive occurrences of a [4+2] intramolecular Diels-Alder reaction and a symmetry-allowed [4+4] photocyclization to afford hexacyclic enone **8** and pentacyclic diene **9** in 15% and 50% yields, respectively. Thermolytic reaction of dione **7** resulted in the formation of enone **8** in over 80% yield.[3] In the presence of maleic anhydride, thermolysis of dione **7** was accompanied with a domino Diels-Alder reaction affording adduct **10**, which was used in this laboratory to synthesize C_{2v} symmetric hexacyclic diene **11**.[4b] In a continuation of our interest in the synthesis and chemistry of polycyclic cage compounds,[4,10] we prepared *endo*,*syn*,*endo*-diol **3a** and converted it via a similar process of dechlorination-hydrolysis followed by acetylation to decahydro-11,12-dioxo[1,4;5,8]-dimethano anthracene-9,10-diol diacetate **22**, the derivative of pentacyclic dione **7** (Scheme V). We thought the products attained from **22** via photolysis and thermolysis, having the ring skeletons as pentacyclic dienes **8**, **9**, and **11**, could be elaborated as precursors toward novel polycyclic cage compounds related to iceane (**12**),[11] the elusive hexaprismane (**13**),[12] and hitherto unknown **14**. Tetraene **14** is a pentacyclic $C_{16}H_{16}$ hydrocarbon having two pairs of double bonds orthogonally disposed. Conceptually, it is a dimer of cyclooctatetraene (**15**) via a [2+2+2+2] cycloaddition and synthetically it conceivably could be realized by ring expansion of pentacyclic dione **16**, which is a diketonic deriv-

Scheme II



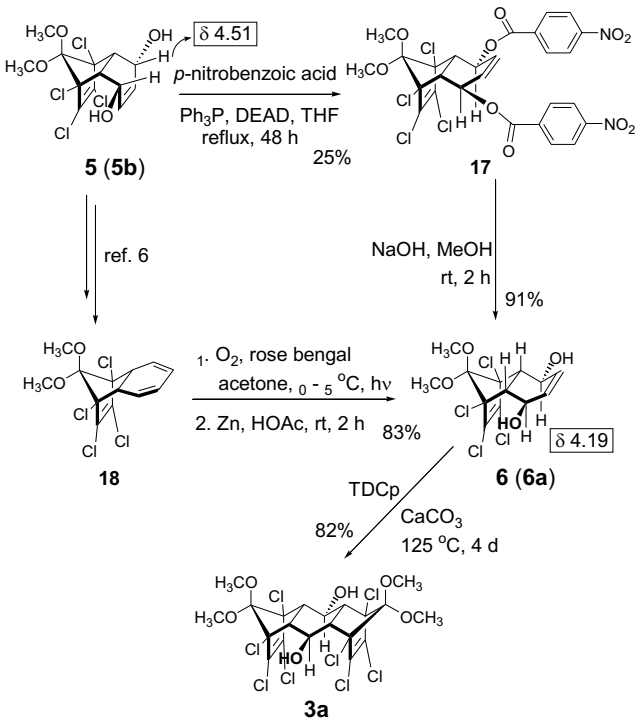
ative of pentacyclic diene **9**, and is the main target molecule pursued in this work. With this intention and investigating the effects of the presence and configuration of acetoxy groups on the thermolytic and photolytic behavior shown in Scheme II, we also attempted, yet unsuccessfully, to synthesize diacetoxy dione **27**, which is the stereoisomer of dione **22** having two acetoxy groups located inside the cavity between the two etheno-bridge double bonds. This paper describes the results.



RESULTS AND DISCUSSION

The configurational inversion of carbon atoms bearing hydroxyl groups in *endo*,*endo*-diol **5**[6] to form *exo*,*exo*-diol **6** was accomplished via two routes as outlined in Scheme III. The Mitsunobu protocol[13] (Ph_3P, DEAD) utilizing *p*-nitrobenzoic acid as the nucleophile was employed.[7] Di-*p*-nitrobenzoate **17** thereby obtained in 25% yield was subsequently hydrolyzed to furnish diol **6** in 23% overall yield. Obviously, the low yield of di-*p*-nitrobenzoate **17** was due to the steric hindrance present in both conformations of diol **5**. Alternatively, via the route also utilized in another laboratory,[9] diol **5** was first subjected to a NaI-promoted 1,4-elimination via its corresponding dimesylate to generate cyclohexadiene **18**.[6] Compound **18** was then converted to diol **6** by adding singlet oxygen to the exo face of cyclohexadiene **18** (using rose bengal as sensitizer)

Scheme III

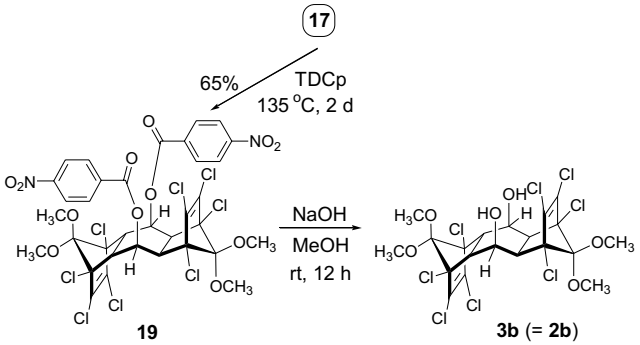


followed by reducing the resulting endoperoxide with zinc dust in acetic acid a route of more work, but of higher rewards in terms of the overall yields.[14] Diels-Alder reactions of diol **6** with TDCp in the presence of $CaCO_3$ constantly furnished *endo*,*syn*,*endo*-diol **3a** in yields of more than 80% without contamination with another stereoisomer **3b**.[8,15]

At the time we were successful in inverting the configuration of hydroxy group-bearing carbon atoms in *endo*, *endo*-diol **5** and established the structure of *exo*,*exo*-diol **6**,[7] Forman and Dailey reported the attainment of diol **6** via the abovementioned second route and successfully carried out the Diels-Alder reaction of diol **6** with TDCp to form *endo*,*syn*,*endo*-diol **3a** in their synthetic approach toward hexaprismane and heptaprismane.[9] The results from these two laboratories supported our speculation of the conformational preference and the conformation-controlled π-facial selectivity in the Diels-Alder reactions of diols **5** and **6** (Scheme I). The conformational preference of these two diols was also suggested by the difference in ^{1}H NMR chemical shifts displayed by the hydrogens at the hydroxy group-bearing carbons. The α-hydrogens at carbons bearing hydroxyl groups in diol **6** displayed a broad signal at δ 4.19, which is at higher field by about 0.32 ppm than the broad signal (δ 4.51)[6] displayed by the corresponding α-hydrogens in diol **5** (Scheme III). The upfield shift exhibited by the α-hydrogens is attributed to the consequence of anisotropic shielding effect on the inward α-hydrogens by the face-to-face juxtaposed dichlorinated double bond,[16,17] a situation which occurs only in the "unfolded" boat-conformation **6a**.

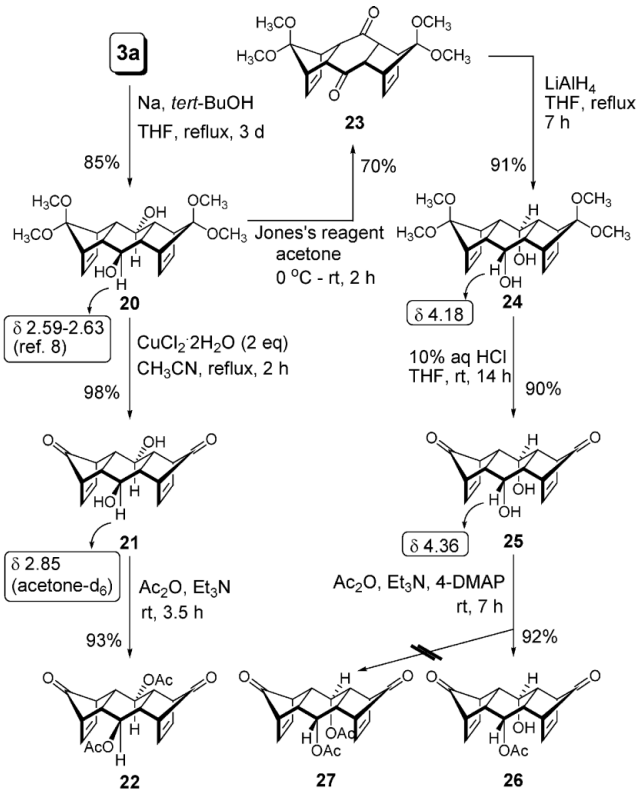
Expecting that the steric interaction between cis-oriented groups of more bulky size would increase in the "folded" conformation resembling **6b**, we thought that the conformational preference of dibenzoyloxy derivative **17** for the "unfolded" conformation similar to **6a** would be enhanced, and accordingly the conformation-controlled π-facial selectivity in the Diels-Alder reaction of **17**. As shown in Scheme IV, di-*p*-nitrobenzoate **17** behaved like diol **6** to undergo the Diels-Alder reaction with TDCp only at rather harsh temperature (125-135 °C) as a neat mixture; however, the reaction surprisingly furnished the adduct of opposite configuration, the *endo,anti,endo*-adduct **19** in 65% yield.[18] The determination of the structure of adduct **19** was supported by transformation to the corresponding diol **3b** (= **2b**) via hydrolysis. Presumably, steric congestion in the transition state of the reaction of TDCp and the "folded" conformation of **17** was less severe than that of TDCp and the "unfolded" conformation of **17**, in which the existing and developing dichlorinated double bonds flanked the two bulky benzoyloxy groups.

Scheme IV



Endo,*syn*,*endo*-diol **3a** was then subjected to reductive dechlorination (Na/*tert*-BuOH) in refluxing THF to afford bis-acetal diol **20**[9] in 85% yield (Scheme V). When diketal diol **20** was treated with $CuCl_2 \cdot H_2O$ in refluxing acetonitrile for 2 h,[19] the reaction provided a quantitative yield of diketonic diol **21**,[9] which was subsequently subjected to acetylation (Ac_2O/Et_3N) to furnish the diketonic

Scheme V

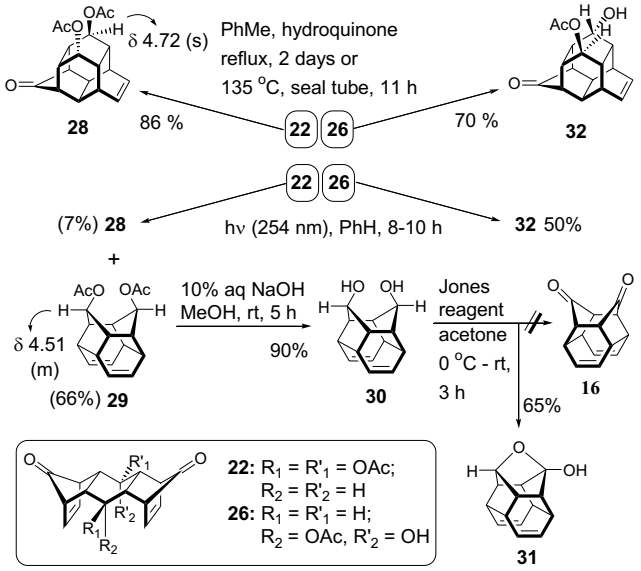


diacetate **22** in 93% yield. The structure of **22** was suggested by the elemental analysis in accordance with the molecular formula $C_{20}H_{20}O_6$ and supported by the spectral data, in which a six-hydrogen singlet at δ 2.08 in the ^{1}H NMR spectrum and a signal at δ 169.8 in the ^{13}C NMR spectrum indicated the presence of two acetoxy groups. The presence of ketonic functional groups in **22** were revealed by a strong absorption band at 1779 cm^{-1} in the IR spectrum and a signal at δ 201.0 in the ^{13}C NMR spectrum, which are characteristics of a bicyclo[2.2.1]heptan-7-one unit. The outward orientation of two acetoxy groups in diacetate **22** is inherited from *endo*,*syn*,*endo*-diol **3a** and is maintained throughout its synthesis. For structural and property comparison, we prepared the known diketal dione **23**[9] by oxidation of diketal diol **22** using Jones reagent, and anticipated that the metal-hydride reduction would occur at the convex side (anti to the carbon-carbon double bond) of dione **23** to deliver a diol having the two hydroxyl groups placed inside the cavity and sandwiched by two double bonds.

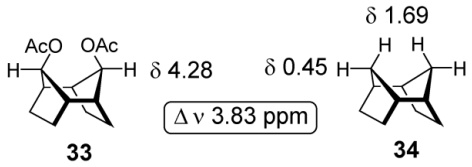
Thus, as illustrated in Scheme V, reduction of dione **23** in THF with $LiAlH_4$ gave diketal diol **24** in 91% yield. Structurally isomeric to diketal diol **20**, as indicated by the mass spectral and elemental analytical data, diketal diol **24** shows inverted configurations for carbons bearing hydroxyl groups (relative to those in **20**) as indicated by the ^{1}H NMR spectrum in $CDCl_3$. The α-hydrogens at carbons bearing hydroxyl groups in diketal diol **24** display a broad signal at δ 4.18 (δ 4.06 in acetone-d_6), which is at lower field by about 1.5 ppm than the multiplet (δ 2.59-2.63 ppm)[9] displayed by the corresponding α-hydrogens in diketal diol **20**. Again, the upfield shift exhibited by the α-hydrogens in diketal diol **20** is attributed to the consequence of anisotropic shielding effect on the inward α-hydrogens by the two face-to-face juxtaposed double bonds across the cyclohexadiol ring and is well demonstrated in other similar compounds reported[16] and prepared in this laboratory.[17] A similar difference in chemical shifts exhibited by these α-hydrogens in isomeric diketone diols **21** and **25** was also observed (Scheme V). Diketone diol **25** was obtained in 90% yield simply by hydrolysis of diketal diol **24** in THF with 10% aqueous HCl. Attempt of bis-acetylation of **25** (Ac_2O/Et_3N/4-DMAP) led only to the isolation of mono-acetylated diketone **26** in 92% yield, without a noticeable amount of diacetylated product **27**, reflecting the facts that hydroxyl groups are located inside the molecular cavity of diol **25** and the epimerization of diol **20** to diol **24** has been successfully implemented. The structures and the inherent C_{2v} symmetry for all synthetic intermediates were clearly revealed from spectral characteristics, except acetate **26**, which was shown to lose one of the two symmetry elements present in its precursors (see the Experimental Section).

With diacetate **22** and **26** in hand, we started to investigate their thermal and photochemical behavior. As shown in Scheme VI, when a solution of diacetate **22** in toluene was sealed in a reaction tube with hydroquinone and heated at 135 °C for 11 h, thermolysis occurred and an 86% yield of the diacetate **28** was obtained. The ten-line ^{13}C NMR spectrum with two carbonyl carbons (δ 208.1; δ 170.4) and one olefinic carbon (δ 134.9) clearly established the formation of caged diacetate **28** from diacetate **22** via the course of mono-decarbonylation followed by a rapid intramolecular Diels-Alder reaction. However, with maleic anhydride present in the reaction mixture, low yield of caged diacetate **28** in company with yet unidentified complex products was observed in numerous attempts. We did not observe any product derived from intermolecular or domino Diels-Alder cycloaddition to yield the anticipated hexacyclic adduct similar **10** (Scheme II).

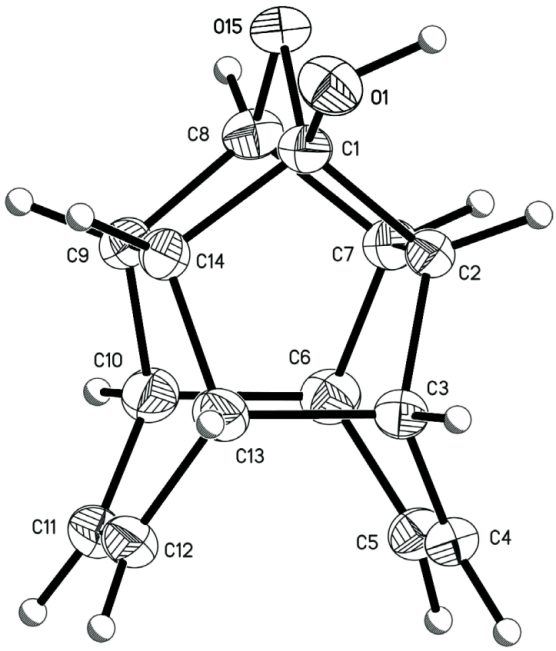
Scheme VI



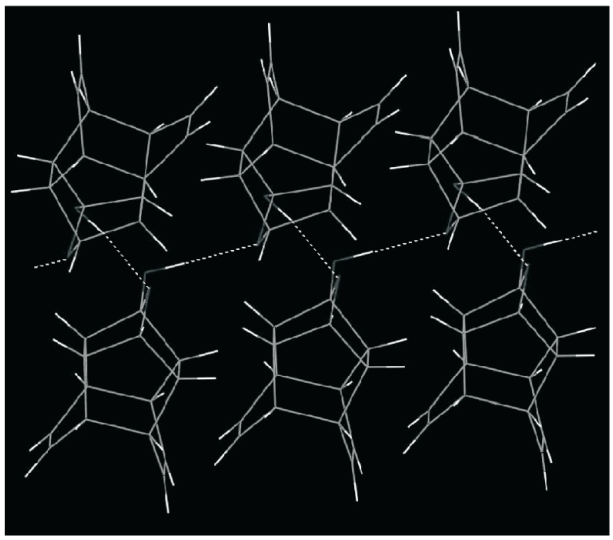
On the other hand as shown in Scheme VI, irradiation (λ 254 nm, Rayonet) of a dilute solution of diacetate **22** in benzene for 10 h furnished two products isolated by chromatography in 7% and 66% yields, respectively. The minor product (**28**) was proved to be identical to the compound obtained from the thermolysis of **22** by spectral and chromatographic comparison. The IR spectrum of the major product did not show a norbornan-7-one type carbonyl absorption band. A six-line ^{13}C NMR spectrum with one olefinic carbon (δ 130.2) and one carboxyl carbon (δ 171.1) for a molecular formula $C_{18}H_{20}O_4$, together with a ^1H NMR spectrum containing only five groups of chemically non-equivalent hydrogens, clearly indicated the presence of C_{2v} symmetry in molecular structure. These spectral data also suggested the skeleton of diacetyl diene **29**, the major product obtained from the photolysis of **22**, was similar to that of pentacyclic diene **9** (Scheme II), which resulted from the occurrence of double decarbonylation with concomitant [4+4] photocyclization. The stereochemistry of the two acetoxy groups was maintained in the thermolysis and photolysis of **22** leading to the formation of **28** and **29**. These acetoxy groups in **28** and **29** of occupy the endo positions, directing inward the boat-form cyclohexane ring, as supported by the differences in chemical shifts (Δν) for the geminal exo hydrogens between **28** (δ 4.72) and **29** (δ 4.51) and their respective parent compounds **8** and **9** (**28** *vs*. **8**: Δν 3.45 ppm; **29** *vs* **9**: Δν 3.66 ppm), which are comparable with those between diacetate **33** and its parent compound **34** (Δν 3.83 ppm).[20] On the contrary, although mono-acetylated diketone **26** gave a comparable result to **22** upon thermolysis, yielding caged monoacetate **32** in 70% yield via the course of mono-decarbonylation followed by a rapid intramolecular Diels-Alder reaction, **26** did not undergo a symmetry-allowed [4+4] photocyclization under the same conditions. The photochemical reaction was found to give a complicated mixture of products from which only the caged monoacetate **32** could be isolated in 50% yield (Scheme VI).



Hydrolysis of diacetoxy diene **29** with NaOH in methanol gave the corresponding diol **30** in 90% yield. Upon oxidation with Jones reagent in acetone, diol **30** underwent a fast transannular reaction to afford bridged hemiacetal **31** in 65% yield, without the desired dione **16** (Scheme V). Hemiacetal **31** showed high stability and could not be opened to hydroxyl-ketone form by hydrolysis, resisted further oxidation to **16**, and refused to go back to diol **30** upon reduction with $LiAlH_4$. The elemental analysis and spectral characteristics, particularly the broad absorption band at 3250 cm^{-1} in the IR spectrum and signals at δ 115.2 (s) and δ 79.3 (d) in the ^{13}C NMR spectrum, supported the structure of hemiacetal **31**. The structure was further analyzed and unambiguously established by single-crystal X-ray crystallography (Fig. 1). A suitable single crystal of hemiacetal **31** was obtained by crystallization from acetone-CH_2Cl_2 in orthorhombic space group Pbca. Fig. 1A shows the ORTEP plots of molecular structures for **31**. Analysis of the molecular structure reveals that the overall geometry of **31** is, in general, comparable to that of similar caged compounds.[10a] An elongated carbon-carbon bond length of 1.6103 (17) Å for C3-C13 (C6-C10) is observed. The dihedral angle for C3-C4-C5-C6 and C10-C11-C12-C13 planes is 49.7°, resulting in a separation of carbon-carbon double bond by a distance of 2.875 Å and an interorbital angle of 130.3°. The major force to support crystal packing is the intermolecular hydrogen bonding between hemiacetal moieties with an O···H distance of 1.85 Å and an O-H···O angle of 168.5° (Fig. 1B).



(A)



(B)

Fig. 1. (A) The ORTEP drawing for molecular structure of **31** and (B) part of crystal structure of **31**, showing the formation of hydrogen-bonded array (yellow dashed lines, d = 1.85 Å; angle 168.5°).

CONCLUSION

We have demonstrated the conformation-controlled π-facial selectivity in the Diels-Alder reactions of 1,2,3,4-tetrachloro-5,5-dimethoxycyclopentadiene (TDCp) with stereoisomeric 5,6,7,8-tetrachloro-1,4,4a,5,8,8a-hexahydro-9,9-dimethoxy-5,8-methanonaphthalene-1,4-diols, **5** and **6**. *Endo*,*endo*-diol **5** and *exo*,*exo*-diol **6** appeared to have different conformational preferences determined by the configurations of carbon atoms bearing hydroxy groups, and thus afforded *endo*,*anti*,*endo*-adduct **2b** and *endo*, *syn*,*endo*-adduct **3a**, respectively (Scheme I). Two routes were employed to achieve the configurational inversion of hydroxy-bearing carbon atoms in diol **5**, which involved directly Mitsunobu protocol and in a roundabout way via the endoperoxide of cyclohexadiene **13** prepared from diol **5** (Scheme III). The thermolysis of diacetate **22** produced *endo,endo*-3,6-diacetoxyhexacyclo[6.6.1.0^{2,7}.0^{4,13}.0^{5,10}.0^{9,14}]-pentadeca-11-en-15-one (**28**), resulting from decarbonylation with successive occurrences of a [4+2] intramolecular Diels-Alder reaction. The photolysis of diacetate **22** was found to produce, in addition to enone **28**, *endo,endo*-2.9-diacetoxypentacyclo[8.4.0.0^{3,8}.0^{4,14}.0^{7,11}]tetradeca-5,12-diene (**29**), resulting from decarbonylation with successive occurrences of a symmetry-allowed [4+4] photocyclization (Scheme VI). Synthesis of **27**, the stereoisomer of dione **22**, having two acetoxy groups located inside the cavity between the two etheno-bridge double bonds was not successful. Only the corresponding monoacetate **26** was obtained, which upon thermolysis and photolysis gave only hexacyclic enone **32**. Pentacyclic diacetate **29** was converted by hydrolysis to the title diendiol **30**, which upon oxidation afforded stable hexacyclic bridged hemiacetal **31** as a result of facile transannular reaction and accordingly precluded our pursuit of tetraene **14** via diketonic precursor **16** (Scheme VI). The structure of hemiacetal **26** was analyzed by single-crystal X-ray crystallography.

EXPERIMENTAL SECTION

General

Melting points were determined in capillaries on a Thomas-Hoover or Büchi Melting Point B-540 apparatus and are uncorrected. Infrared (IR) spectra were recorded on a JASCO 400-plus or Perkin-Elmer 682 spectrophotometer as a solid suspended in a KBr disk. ^{1}H and ^{13}C NMR spectra were collected on a Brüker DPX-400 or Varian Unity-300 spectrometer using $CDCl_3$ as solvent (unless otherwise specified). Coupling constants are reported in hertz. The number of attached hydrogens on the carbon atom was determined by DEPT analysis. The assignment of proton and

carbon NMR peaks was supported by ^{1}H-^{1}H COSY and HMQC spectra and for some compounds in addition by NOESY spectra. Mass (MS) spectra were obtained on a VG Trio-2000 GC/MS or TRIO-2000 GC-MS instrument by the EI mode unless otherwise indicated. All solvents used were either reagent grade or were distilled prior to use. Analytical thin-layer chromatography (TLC) was performed on E. Merck silica gel 60 F_{254} plate (0.20 mm). Flash chromatography was performed on E. Merck silica gel (230-400 mesh). Microanalyses were performed by the NSC Analytical Centers operated by Cheng Kung University, Tainan, or Chung Hsing University, Taichung, Taiwan.

(lα,4α,4aβ,5β,8β,8aα,9β,9aβ,10β,10aα)-1,2,3,4,5,6,7,8-octachloro-1,4,4a,5,8,8a,9,9a,10,10a-decahydro-11,11,12,12-tetramethoxy-[1,4;5,8]dimethanoanthracene-9,10-diol (2b)

A solution of enediol **5**[6] (1.0 g, 2.7 mmol) and TDCp (0.7 g, 2.7 mmol) in xylene (15 mL) was heated under reflux for 2 days. The resulting white precipitates were collected and recrystallized from acetone to afford adduct **2b** (1.5 g, 85%): mp 270-271 °C; IR (KBr) 3273 (br s), 2857 (m), 1610 (m), 1464 (m), 1188 cm^{-1} (s); ^{1}H NMR (300 MHz, acetone-d_6) δ 4.90 (d, J = 8.4 Hz, 2H, -OH), 4.27 (d, J = 8.4 Hz, 2H), 3.58 (s, 3H), 3.54 (s, 3H), 3.47 (s, 3H), 3.45 (s, 3H), 3.15 (br, 2H), 2.52 (br, 2H); ^{13}C NMR (75.4 MHz, acetone-d_6) δ 130.32 (s), 130.31 (s), 115.78 (s), 115.68 (s), 78.1 (s), 77.4 (s), 61.7 (d), 53.7 (d), 53.3 (q), 53.0 (q), 52.3 (q), 52.1 (q), 49.7 (d); MS (EI, 70 eV) *m/z* (relative intensity) 636 (M^+, 4), 601 (55), 573 (67), 253 (100), 207 (30). Anal. Calcd for $C_{20}H_{20}Cl_8O_6$: C, 37.53; H, 3.15; Cl, 44.32. Found: C, 37.48; H, 3.13; Cl, 44.35.

(lβ,4β,4aβ,5α,8α,8aβ)-5,6,7,8-Tetrachloro-1,4,4a,5,8,8a-hexahydro-9,9-dimethoxy-5,8-methanonaphthalene-1,4-diol Di-*p*-nitrobenzoate (17)

Diethyl azodicarboxylate (0.9 g, 5.3 mmol) was added dropwise into a stirring THF solution (30 mL) containing enediol **5**[6] (1.0 g, 2.7 mmol), triphenylphosphine (1.4 g, 5.3 mmol), and *p*-nitrobenzoic acid (0.9 g, 5.4 mmol). After the addition was completed, the reaction mixture was heated under reflux for 2 days. Removal of solvent left a brown viscous residue, into which methanol (50 mL) was added, and the resultant solution was set aside overnight. The precipitates thereby formed were collected and recrystallized from EtOAc/nHex to give bis-*p*-nitrobenzoate **17** (0.44 g, 25%) as a white crystalline: mp 230-231 °C; IR (KBr) 2955 (m), 1740 (s), 1617 (m), 1536 (s), 1278 (s), 750 cm^{-1} (s); ^{1}H NMR (300 MHz, $CDCl_3$) δ 8.21-8.28 (AA'BB' pattern, 8H), 6.04 (d, J = 1.5 Hz, 2H), 5.55-5.56 (m, 2H), 3.71 (s, 3H), 3.59 (s, 3H), 3.42 (d, J = 3.6 Hz, 2H); ^{13}C NMR (75.4 MHz, $CDCl_3$) δ 163.6 (s), 150.8 (s), 135.1 (s), 130.9 (d), 130.1 (d), 129.8 (s), 123.6 (d), 111.7 (s), ~ 77 (s, hidden, C–Cl), 67.1 (d), 53.1 (q), 52.1 (q), 49.4 (d); MS (EI, 70 eV) *m/z* (relative intensity) 672 (M^+, 3), 637 (92), 472 (35), 303 (100), 257 (35), 194 (15), 150 (97), 104 (48). Anal. Calcd for $C_{27}H_{20}Cl_4N_2O_{10}$: C, 48.10; H, 2.99; Cl, 21.03; N, 4.15. Found: C, 48.32; H, 3.25; Cl, 21.03; N, 4.01.

(lβ,4β,4aβ,5α,8α,8aβ)-5,6,7,8-tetrachloro-1,4,4a,5,8,8a-hexahydro-9,9-dimethoxy-5,8-methanonaphthalene-1,4-diol (6)

Into a stirring solution of bis-*p*-nitrobenzoate **17** (1.0 g, 1.5 mmol) in acetone (5 mL) was added dropwise a MeOH solution (10 mL) of NaOH (0.2 g, 5 mmol). After stirring for 2 h, solvents were removed under reduced pressure to give a gray solid residue, which was mixed with water (20 mL), and extracted with CH_2Cl_2 (15 mL × 2). The combined organic layers were washed successively with saturated sodium carbonate solution (10 mL), water (20 mL), and brine (20 mL), and then dried ($MgSO_4$) and filtered. Removal of solvent under reduced pressure gave solid residue, which was recrystallized from EtOAc/nHex to afford diol **6** (0.5 g, 91%) as colorless crystals: mp 147-148 °C; IR (KBr) 3280 (br s), 2949 (m), 1660 (m), 1448 (w), 1277 cm^{-1} (m); ^{1}H NMR (300 MHz, $CDCl_3$) δ 5.95 (d, J = 2.1 Hz, 2H), 4.19 (br, 2H), 3.64 (s, 3H), 3.56 (s, 3H), 3.08 (m, 2H), 2.51 (br, 2H, -OH); ^{13}C NMR (75.4 MHz, $CDCl_3$) δ 132.1 (d), 129.1 (s), 111.9 (s), ~ 77 (s, hidden, C–Cl), 63.6 (d), 53.0 (d), 52.8 (q), 51.8 (q); MS (EI, 70 eV) *m/z* (relative intensity) 339 (M^+ – Cl – H , 35), 303 (5), 253 (100), 223 (5), 207 (30). Anal. Calcd for $C_{13}H_{14}Cl_4O_4$: C, 41.52; H, 3.75; Cl, 37.71. Found: C, 41.42; H, 3.74; Cl, 37.92.

(lα,4α,4aβ,5α,8α,8aβ,9β,9aβ,10β,10aβ)-1,2,3,4,5,6,7,8-Octachloro-1,4,4a,5,8,8a,9,9a,10,10a-decahydro-11,11,12,12-tetramethoxy-[1,4;5,8]dimethanoanthracene-9,10-diol (3a)[9]

A mixture of enediol **6** (1 mmol) and TDCp (1.05 mmol) was heated at 125 °C for 2 days in the presence of a catalytic amount of $CaCO_3$. After the reaction mixture was cooled to room temperature, the reaction mixture was dis-

solved in hot ethanol and decolorized with activated charcoal and filtered through a pad of Celite. The filtrate was concentrated under reduced pressure to give crude product, which was recrystallized from dichloromethane to afford pure **3a** (82-86%): mp 206-207 °C; IR (KBr) 3515 (br, m), 2954 (m), 1604 (m), 1278 (m), 1192 cm^{-1} (s); ^1H NMR (300 MHz, $CDCl_3$) δ 3.60 (s, 3H), 3.56 (s, 3H), 3.27-3.38 (m, 2H), 2.82-2.85 (m, 4H), 2.36 (d, J = 2.7 Hz, 2H, -OH); ^{13}C NMR (75.4 MHz, $CDCl_3$) δ 129.5 (s), 111.0 (s), ~ 77 (s, hidden, C–Cl), 66.6 (d), 52.7 (q), 51.9 (q), 51.9 (d); MS (EI, 70 eV) *m/z* (relative intensity) 636 (M^+, 1), 603 (100), 253 (11), 207 (10).

(lα,4α,4aβ,5β,8β,8aα,9β,9aβ,10β,10aα)-1,2,3,4,5,6,7,8-octachloro-1,4,4a,5,8,8a,9,9a,10,10a-decahydro-11,11,12,12-tetramethoxy-[1,4;5,8]dimethanoanthracene-9,10-diol Di-*p*-nitrobenzoate (19)

A mixture of bis-*p*-nitrobenzoate **17** (0.1 g, 0.15 mmol) and TDCp (2 mL) was heated at 130 °C for 2 days. After the reaction mixture was cooled to room temperature, the reaction mixture was chromatographed on a silica gel column (EtOAc/nHex 1:5) and recrystallized from EtOAc to furnish pure adduct **19** (0.09 g, 65%): mp 279-280 °C; IR (KBr) 1737 (s), 1600 (m), 1530 (s), 1261 (s), 1194 cm^{-1} (m); ^1H NMR (300 MHz, acetone-d_6) δ 8.40 (AA'BB' pattern, 8H), 5.39-5.44 (m, 2H), 3.85 (br, 2H), 3.72 (s, 3H), 3.54 (s, 3H), 3.53 (s, 3H), 3.50 (d, J = 3 Hz, 2H), 3.47 (s, 3H); ^{13}C NMR (75.4 MHz, acetone-d_6) δ 162.9 (s), 151.0 (s), 134.9 (s), 131.3 (d), 130.3 (s), 123.8 (d), 115.6 (s), 116.9 (s), 77.4 (s), 76.3 (s), 68.7 (d), 52.4 (q), 52.1 (q), 51.7 (q), 51.6 (q), 47.5 (d), 46.2 (d); MS (EI, 70 eV) *m/z* (relative intensity) 940 (M^+, 1), 903 (100), 901 (90), 865 (40), 770 (52), 736 (30), 605 (35). Anal. Calcd for $C_{34}H_{26}Cl_8N_2O_{12}$: C, 43.53; H, 2.79; Cl, 30.23; N, 2.99. Found: C, 43.76; H, 3.03; Cl, 30.2; N, 3.00.

Bis-*p*-nitrobenzoate adduct **19** was hydrolyzed by stirring in methanol with NaOH for 12 h to give diol adduct **3b** in quantitative yield (95%), which was analyzed to be identical to the adduct **2b** obtained from the Diels-Alder reaction of TDCp with enediol **5**.

(lα,4α,4aβ,5α,8α,8aβ,9β,9aβ,10β,10aβ)-1,4,4a,5,8,8a,9,9a,10,10a-Decahydro-11,12-dioxo-[1,4;5,8]dimethanoanthracene-9,10-diol (21)

To a solution of diol bis-acetal **20**[9] (3.72 g, 10.2 mmol) in MeCN (50 mL) was added $CuCl_2 \cdot 2H_2O$ (3.48 g, 20.4 mmol). The mixture was heated under reflux and the progress of the reaction was monitored by TLC (EtOAc/nHex 4:1). When the reaction was complete (2 h), the reaction mixture was cooled to room temperature, and the solvent was removed under reduced pressure to give a brown solid residue, which was purified by flash chromatography on a silica gel column (EtOAc/nHex 4:1; R_f = 0.60) and recrystallized from EtOAc to furnish diol diketone **21** (2.72 g, 98%) as white powder: mp 175-176 °C; IR (KBr) 3593 (s), 3243 (br), 2930 (m), 1774 (s), 1664 (m), 1374 (m), 1337 (m), 1056 (s), 720 cm^{-1} (m); ^1H NMR (400 MHz, acetone-d_6) δ 6.55 (dd, J = 2.3, 2.3 Hz, 4H), 4.14 (d, J = 5.6 Hz, 2H), 3.03-3.01 (m, 4H), 2.86-2.84 (m, 2H), 2.39-2.35 (m, 4H); ^{13}C NMR (100 MHz, acetone-d_6) δ 204.4 (s), 133.6 (d), 68.0 (d), 51.4 (d), 44.1 (d); MS (EI, 70 eV) *m/z* (relative intensity) 272 (M^+, 7), 244 (M^+-28, 21), 226 (11), 208 (15), 145 (32), 128 (27), 115 (36), 107 (64), 91 (100). Anal. Calcd for $C_{16}H_{16}O_4$: C, 70.57; H, 5.92. Found: C, 70.66; H, 6.07.

(lα,4α,4aβ,5α,8α,8aβ,9β,9aβ,10β,10aβ)-1,4,4a,5,8,8a,9,9a,10,10a-Decahydro-11,12-dioxo-[1,4;5,8]dimethanoanthracene-9,10-diol Diacetate (22)

A mixture of diketonic diol **21** (0.153 g, 0.53 mmol), Et_3N (0.8 mL, 5.74 mmol), and acetic anhydride (0.8 mL, 8.5 mmol) was stirred at room temperature under a nitrogen atmosphere for 3.5 h (monitored by TLC). The reaction mixture was then cooled with an ice bath and ice-cold water was then added (20 mL), and extracted with dichloromethane (10 mL × 3). The combined extracts were washed in sequence with saturated aqueous $NaHCO_3$ (20 mL), water (20 mL), and brine, then dried ($MgSO_4$) and filtered. The solvent was removed under reduced pressure to give a pale yellow solid residue, which was purified by recrystallization from CH_2Cl_2/Ether (1:1) to afford diacetate **22** (0.186 g, 93%) as colorless flakes: mp 178-179 °C; IR (KBr) 2958 (w), 2921 (w), 1779 (s), 1747 (s), 1659 (w), 1236 (s), 1033 (s), 729 cm^{-1} (s); ^1H NMR (400 MHz, $CDCl_3$) δ 6.53 (dd, J = 2.3, 2.3 Hz, 4H), 4.30-4.25 (m, 2H), 2.85-2.83 (m, 4H), 2.59-2.56 (m, 4H), 2.08 (s, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 201.0 (s), 169.8 (s), 132.5 (d), 69.1 (d), 49.3 (d), 40.0 (d), 20.9 (q); MS (EI, 70 eV) *m/z* (relative intensity) 357 (M^++1, w), 328 (M^+-28, 10), 268 (16), 240 (13), 226 (16), 209 (18), 208 (100), 179 (57), 165 (32), 128 (87), 115 (21), 107 (64), 91 (93), 77 (27). Anal. Calcd for $C_{20}H_{20}O_6$: C, 67.40; H, 5.65. Found: C, 67.15; H,

5.62.

(lα,4α,4aβ,5α,8α,8aβ,9α,9aβ,10α,10aβ)-1,4,4a,5,8,8a,9,9a,10,10a-Decahydro-11,11,12,12-tetramethoxy-[1,4;5,8]dimethanoanthracene-9,10-diol (24)

Into a stirring solution of bis-acetal dione **23**[9] (3.34 g, 9.34 mmol) in dried THF (50 mL) under N_2 atmosphere at 0 °C was added $LiAlH_4$ (1.75 g, 46.1 mmol) in portions. The reaction mixture was then allowed to warm up to room temperature and gently heated at refluxing temperature for 7 h. After the reaction mixture was cooled down to 0 °C, ice-cold water (2 mL) was carefully added followed by addition of 10% HCl solution (20 mL), and then extracted with dichloromethane (100 mL × 3). The combined extracts were washed sequentially with saturated aqueous $NaHCO_3$ (50 mL), water (50 mL), and brine, then dried ($MgSO_4$) and filtered. The solvent was removed under reduced pressure to give a pale yellow solid residue. Recrystallization of solids from acetone afforded bis-acetal diol **24** (3.07 g, 91%) as white prisms: mp 196-197 °C; IR (KBr) 3464 (s), 3280 (br), 3079 (m), 2967 (s), 2898 (s), 2829 (m), 1469 (m), 1269 (s), 1100 (s), 1066(s), 709 cm^{-1} (m); ^1H NMR (400 MHz, acetone-d_6) δ 5.87 (dd, J = 2.0, 2.0 Hz, 4H), 4.06 (br, 2H), 3.43 (d, J = 8.3 Hz, 2H), 3.14 (s, 6H), 3.01 (s, 6H), 2.73 (br, 4H), 2.45 (br, 4H); ^{13}C NMR (100 MHz, acetone-d_6) δ 131.6 (d), 119.8 (s), 68.3 (d), 51.8 (q), 49.7 (q), 48.8 (d), 46.1 (d); MS (EI, 70 eV) *m/z* (relative intensity) 364 (M^+, 27), 349 (M^+- Me, 7), 333 (M^+- OMe, 9), 151 (100), 91 (32), 58 (40). Anal. Calcd for $C_{20}H_{28}O_6$: C, 65.91; H, 7.74. Found: C, 65.80; H, 7.75.

(lα,4α,4aβ,5α,8α,8aβ,9α,9aβ,10α,10aβ)-1,4,4a,5,8,8a,9,9a,10,10a-Decahydro-11,12-dioxo-[1,4;5,8]dimethanoanthracene-9,10-diol (25)

To a stirring solution of bis-acetal diol **24** (1.36 g, 3.74 mmol) in THF (20 mL) cooled at 0 °C was added dropwise 10% HCl solution (2 mL). After stirring at room temperature (monitored by TLC) for another 14 h, the reaction mixture was then extracted with dichloromethane (50 mL × 3). The combined extracts were washed successively with saturated aqueous $NaHCO_3$ (30 mL), water (50 mL), and brine, then dried ($MgSO_4$), filtered, and concentrated under reduced pressure. The resulting pale yellow residue was recrystallized from acetone to give dihydroxy dione **25** (0.92 g, 90%) as white powder: mp 131-133 °C; IR (KBr) 3180 (br), 2894 (m), 1767 (s), 1492 (m), 1119 (m), 1092 (m), 1017 (m), 836 cm^{-1} (w); ^1H NMR (400 MHz, $CDCl_3$) δ 6.45 (dd, J = 2.4, 2.4 Hz, 4H), 4.36 (d, J = 7.9 Hz, 2H), 3.06 (br, 4H), 2.59 (br, 4H), 2.53 (d, J = 7.9 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 199.0 (s), 129.9 (d), 67.4 (d), 50.4 (d), 42.2 (d); MS (EI, 70 eV) *m/z* (relative intensity) 272 (M^+, 4), 244 (M^+- 28, 63), 165 (42), 130 (50), 107 (55), 90 (42), 78 (46), 77 (100). Anal. Calcd for $C_{16}H_{16}O_4$: C, 70.57; H, 5.92. Found: C, 70.66; H, 5.96.

(lα,4α,4aβ,5α,8α,8aβ,9α,9aβ,10α,10aβ)-1,4,4a,5,8,8a,9,9a,10,10a-Decahydro-11,12-dioxo-10-hydroxy-[1,4;5,8]dimethanoanthracene-9-ol Acetate (26)

A mixture of dihydroxy dione **25** (304 mg, 1.12 mmol), triethylamine (2.8 mL, 20.1 mmol), acetic anhydride (3.2 mL, 33.4 mmol), and a catalytic amount of 4-DMAP (10 mg) was stirred at room temperature under a N_2 atmosphere for 7 h. The resultant mixture was cooled to 0 °C with an ice-water bath, ice-water (20 mL) was added, and then extracted with CH_2Cl_2 (10 mL × 3). The combined organic layers were washed sequentially with saturated sodium carbonate solution (20 mL), water (20 mL), and brine (20 mL). The solution was dried ($MgSO_4$), filtered, and concentrated to leave a yellow residue, which was recrystallized from CH_2Cl_2 to afford monoacetate **26** (322 mg, 92%) as colorless crystalline: mp 146-147 °C (decomp.); IR (KBr) 3526 (s), 2917 (m), 1769 (s), 1745 (s), 1223 (s), 1199 (s), 693 cm^{-1} (s); ^1H NMR (400 MHz, $CDCl_3$) δ 6.58 (dd, J = 6.4, 3.8 Hz, 2H), 6.10 (dd, J = 6.5, 3.6 Hz, 2H), 5.72 (t, J = 3.9 Hz, 1H), 4.26 (dt, J = 13.2, 4.1 Hz, 1H), 3.10 (dd, J = 3.2, 3.2 Hz, 2H), 2.99 (dd, J = 3.1, 3.1 Hz, 2H), 2.69 (ddd, J = 11.8, 3.7, 3.7 Hz, 2H), 2.61 (ddd, J = 11.8, 3.8, 3.8 Hz, 2H), 2.18 (d, J = 13.2 Hz, 1H), 2.04 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 198.1 (s), 168.6 (s), 132.5 (d), 127.5 (d), 67.0 (d), 66.9 (d), 50.5 (d), 49.7 (d), 41.7 (d), 40.2 (d), 22.1 (q); MS (EI, 70 eV) *m/z* (relative intensity) 314 (M^+, w), 286 (M^+- 28, 1), 198 (14), 120 (19), 91 (100), 79 (54), 77 (38). Anal. Calcd for $C_{18}H_{18}O_5$: C, 68.77; H, 5.77. Found: C, 68.85; H, 6.02.

General procedure for photolysis of diketones 22 and 26

A solution of diketonic compound (0.5 mmol) in benzene (200 mL, concentration ~ 2 mM) was stirred and irradiated with UV-light in a Rayonet apparatus (λ 254 nm) for 8-10 h. (monitored by TLC). The solvent was then removed

under reduced pressure, and the resultant solid residue was analyzed for the presence and ratio of the products by ^{1}H NMR. Chromatography on a silica gel column (EtOAc/nHex 1:2 or 1:4) was followed by recrystallization to afford pure product(s). Photolysis of diketones **22** for 10 h furnished hexacyclic ketone **28** and pentacyclic diene **29** in 7% and 66% yields, respectively. Photolysis of diketones **26** for 8 h afforded hexacyclic ketone **32** as sole tractable product in 50% yield.

***endo,endo*-3,6-Diacetoxyhexacyclo[6.6.1.0^{2,7}.0^{4,13}.0^{5,10}.0^{9,14}]-pentadeca-11-en-15-one (28)**

Mp 170-172 °C; IR (KBr) 2921 (m), 1779 (s), 1728 (s), 1659 (w), 1254 (s), 1038 cm^{-1} (s); ^{1}H NMR (400 MHz, $CDCl_3$) δ 6.40 (dd, *J* = 4.7, 3.1 Hz, 2H), 4.72 (s, 2H), 2.66-2.63 (m, 2H), 2.53 (br, 2H), 2.19-2.17 (m, 2H), 2.05 (s, 6H), 1.96 (br, 2H),1.82 (br, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 208.1 (s), 170.4 (s), 134.9 (d), 72.6 (d), 46.0 (d), 37.3 (d), 33.6 (d), 30.7 (d), 30.1 (d), 21.5 (q); MS (EI, 70 eV) *m/z* (relative intensity) 328 (M^+, 34), 268 (17), 208 (100), 198 (18), 179 (50), 165 (21), 128 (61), 107 (38), 91 (62), 79 (29), 69 (42). Anal. Calcd for $C_{19}H_{20}O_5$: C, 69.50; H, 6.14. Found: C, 69.83; H, 5.89.

***endo,endo*-2.9-Diacetoxypentacyclo[8.4.0.0^{3,8}.0^{4,14}.0^{7,11}]-tetradeca-5,12-diene (29)**

Mp 139-140 °C; IR (KBr) 2965 (m), 1723 (s), 1651 (w), 1242 (s), 1083 (s), 815 cm^{-1} (m); ^{1}H NMR (400 MHz, $CDCl_3$) δ 5.87 (dd, *J* = 5.3, 3.0 Hz, 4H), 4.53-4.49 (m, 2H), 2.82 (br, 4H), 2.36 (br, 4H), 2.12 (s, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 171.1 (s), 130.2 (d), 71.7 (d), 42.3 (d), 39.0 (d), 21.8 (q); MS (EI, 70 eV) *m/z* (relative intensity) 300 (M^+, 4), 284 (17), 240 (17), 214 (20), 180 (56), 179 (100), 178 (41), 165 (22), 91 (20). Anal. Calcd for $C_{18}H_{20}O_4$: C, 71.98; H, 6.71. Found: C, 71.79; H, 6.80.

***exo*-3-Acetoxy-*exo*-6-hydroxyhexacyclo-[6.6.1.0^{2,7}.0^{4,13}.0^{5,10}.0^{9,14}]pentadeca-11-en-15-one (32)**

Mp 179-182 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 6.41-6.46 (m, 2H), 5.41-5.44 (t, 1H), 4.53-4.55 (t, 1H), 2.96 (d, *J* = 3.4, 1H), 2.78 (d, *J* = 3.36, 1H), 2.52-2.54 (m, 2H), 2.29 (d, *J* = 3.36, 1H), 2.18 (d, *J* = 3.44, 1H), 2.07 (s, 3H), 1.97 (s, 1H), 1.96 (s, 1H), 1.92 (s, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 210.95 (s), 170.48 (s), 135.42 (d), 134.86 (d), 68.58 (d), 64.84 (d), 42.26 (d), 41.62 (d), 36.56 (d), 33.64 (d), 33.46 (d), 30.60 (d), 29.94 (d), 29.90 (d), 28.02 (d), 26.80 (d), 21.20 (q). Anal. Calcd for $C_{17}H_{18}O_4$: C, 71.31; H, 6.34; Found: C, 71.23; H, 6.66.

General procedure for thermolysis of diketones 22 and 26

A solution of diketonic compound (1 mmol) and a small amount of hydroquinone in toluene (10 mL) in the absence or presence of maleic anhydride (1 – 5 mmol) was sealed in a pressure tube and heated to 135 °C or was stirred and heated under reflux for 2 days. The reaction mixture was cooled to room temperature and concentrated under reduced pressure to leave a solid residue, which was analyzed by ^{1}H NMR and purified by recrystalization from EA/Hexane to afford pure hexacyclic enone **28** (86%) from **22** and **32** (70%) from **26**.

Transformation of pentacyclic diene 29 to bridged hemiacetal 31

***endo,endo*-2.9-Dihydroxypentacyclo[8.4.0.0^{3,8}.0^{4,14}.0^{7,11}]-etradeca-5,12-diene (30)**

Into a stirring solution of pentacyclic diacetate **29** (0.51 g, 1.71 mmol) in MeOH (20 mL) cooled with an ice-water bath was added dropwise a 10% aqueous NaOH solution (5 mL). The resultant solution was stirred at room temperature for 5 h, cooled to 0 °C, and neutralized with 10% aqueous HCl solution. The reaction mixture was extracted with CH_2Cl_2 (10 mL × 3), and the combined organic layers were washed successively with saturated sodium carbonate solution (20 mL), water (20 mL), and brine (20 mL). The solution was then dried ($MgSO_4$), filtered, and concentrated to leave a pale yellow viscous residue, which was recrystallized from CH_2Cl_2/MeOH to afford diol **30** (0.33 g, 90%) as white powder: mp 224-226 °C (decomp.); IR (KBr) 3174 (br), 2942 (m), 1270 (m), 1252 (m), 1114 (s), 808 (m), 680 cm^{-1} (m); ^{1}H NMR (400 MHz, $CDCl_3$) δ 5.84 (dd, *J* = 5.4, 3.0 Hz, 4H), 3.74-3.71 (m, 2H), 2.74 (br, 4H), 2.23-2.21 (m, 4H), 1.63 (br, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 130.4 (d), 71.9 (d), 42.5 (d), 41.7 (d); MS (EI, 70 eV) *m/z* (relative intensity) 216 (M^+, 2), 198 (M^+ -18, 17), 129 (12), 107 (20), 91 (100), 84 (61). Anal. Calcd for $C_{14}H_{16}O_2$: C, 77.75; H, 7.46. Found: C, 77.38; H, 7.59.

15-Oxa-hexacyclo[6.6.1.0^{2,7}.0^{3,13}.0^{6,10}.0^{9,14}]pentadeca-4,11-dien-1-ol (31)

Into a stirring solution of pentacyclic diol **30** (0.30 g, 1.41 mmol) in acetone (20 mL) cooled with an ice-water bath was added dropwise Jones reagent (2 mL). The resulting solution was stirred at room temperature for 3 h, fol-

lowed by addition of isopropanol (2 mL) and an excess amount of $NaHCO_3$. After stirring for an additional 2 h, the reaction mixture was filtered through a pad of celite, and the filtrate was extracted with CH_2Cl_2 (20 mL × 3). The combined organic layers were washed successively with saturated sodium carbonate solution (10 mL), water (10 mL), and brine (10 mL), then dried ($MgSO_4$), filtered, and concentrated to leave a pale yellow viscous residue. Recrystallizing the residue from CH_2Cl_2 afforded hemiacetal **31** (0.19 g, 65%) as colorless flakes: mp 218-220 °C (decomp.); IR (KBr) 3254 (s), 2955 (m), 1632 (w), 1350 (m), 1335 (m), 1050 (m), 695 cm^{-1} (m); ^1H NMR (400 MHz, $CDCl_3$) δ 5.95-5.87 (m, 4H), 4.51 (t, J = 4.8 Hz, 1H), 4.03 (br, 1H), 3.25-3.13 (m, 2H), 2.98-2.85 (m, 2H), 2.52-2.44 (m, 2H), 2.02 (ddd, J = 10.3, 3.3, 2.6 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 131.6 (d), 131.0 (d), 115.2 (s), 79.3 (d), 49.2 (d), 47.8 (d), 43.4 (d), 42.9 (d); MS (EI, 70 eV) *m/z* (relative intensity) 214 (M^+, 16), 169 (11), 141 (15), 116 (10), 91 (100), 77 (27). Anal. Calcd for $C_{14}H_{14}O_2$: C, 78.48; H, 6.58. Found: C, 78.13; H, 6.51.

Crystal structure of bridged hemiacetal 31

Single crystals of **31** suitable for X-ray crystallographic analysis were obtained by crystallization from acetone-dichloromethane. It crystallized in an orthorhombic form, space group Pbca. The X-ray crystallographic data were recorded with a Bruker Smart APEX CCD diffractometer. Graphite monochromatized Mo Kα radiation [λ = 0.71073 Å] and a temperature of 273(2) K were used. The CCD data were processed with SAINT and the structures were solved by direct method (SHELXS-97[21]) and refined on F^2 by full-matrix least-squares techniques (SHELXL-97[22]). The hydrogen atoms were located from the difference Fourier and refined isotropically. Crystallographic data (excluding structure factors) for **26** has been deposited with the Cambridge Crystallographic Data Centre as supplementary publication numbers CCDC 642213. Copies of the data can be obtained, free of charge, on application to CCDC, 12 Union Road, Cambridge CB2 1EZ, UK [fax: +44(0)-1223-336033 or e-mail: deposit@ccdc.cam.ac.uk].

Compound **31**. $C_{14}H_{14}O_2$, monoclinic, space group Pbca, a = 13.2563(15) Å, b = 6.8793(8) Å, c = 22.3324(3) Å; α = 90°, V = 2035.8(4) $Å^3$, Z = 8, D_{calcd} = 1.398 Mg/m^3, crystal size 1.0 × 0.5 × 0.5 mm^3. A total of 16441 reflections ($-17 \le h \le 34$, $-9 \le k \le 9$, $-29 \le l \le 29$) were collected at T = 273(2) K in the range from 1.82 to 28.65°, of which 2510 were unique (R_{int} = 0.1766). All nonhydrogen atoms were refined anisotropically. Hydrogen atoms were placed in calculated idealized positions. The residual peak and hole of electron densities were 0.339 and -0.508 e $Å^{-3}$, respectively. The final R indices [($I>2\sigma(I)$)]: $R(F)$ = 0.0628, w$R(F^2)$ = 0.1531; GOF = 1.059 (for 202 parameters).

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REFERENCES

1. For a recent review: Khan, F. A.; Prabhudas, B.; Dash, J. *J. Prakt. Chem.* **2000**, *342*, 512-517.
2. (a) Akhtar, I. A.; Fray, G. I. *J. Chem. Soc. (C)* **1971**, 28022804. (b) Bratby, D. M.; Fray, G. I. *J. Chem. Soc. Perkin Trans. 1* **1972**, 195-199.
3. Srikrishma, A.; Sunderbabu, G. *J. Org. Chem*. **1987**, *52*, 5037-5039.
4. (a) Chou, T. C.; Liao, K.-C.; Lin, J.-J. *Org. Lett.* **2005**, *7*, 4843-4846. (b) Chou, T. C.; Yang, M. S.; Lin, C. T. *J. Org. Chem*. **1994**, *59*, 661-663.
5. (a) Khan, F. A.; Dash, J. *J. Am. Chem. Soc.* **2002**, *124*, 2424-2425. (b) Khan, F. A.; Prabhudas, B.; Dash, J.; Sahu, N. *J. Am. Chem. Soc.* **2000**, *122*, 9558-9559.
6. Chou, T.-C.; Chiou, J.-H. *J. Chin. Chem. Soc.* **1986**, *33*, 227-234.
7. Wu, S.-C. Master Degree Thesis, Tunghai University: Taichung, Taiwan, R.O.C., 1993.
8. MM2 calculation revealed that **5a** (E_s = 11.88 kcal/mol) is less stable than **5a** (E_s = 6.66 kcal/mol) and **6a** (E_s = 15.02 kcal/mol) is more stable than **6b** (E_s = 22.57 kcal/mol). Molecular mechanics calculation was carried out using Mechanics^R Pro, version 8.0 (CambridgeSoft) within Chem3D Ultra.
9. Forman, M. A.; Dailey, W. P. *J. Org. Chem.* **1993**, *58*, 1501-1507.
10. (a) Chou, T.-C.; Liu, N.-Y. *J. Chin. Chem. Soc.* **2006**, *53*, 1477-1490. (b) Chou, T.-C.; Hwa, C.-L.; Lin, J.-J.; Liao, K.-C.; Tseng, J.-C. *J. Org. Chem*. **2005**, *70*, 9717-9726. (c) Chou, T.-C.; Lin, G.-H. *Tetrahedeon* **2004**, *60*, 7907-7920.
11. Spurr, P. R.; Hamon, D. P. G. *J. Am. Chem. Soc.* **1983**, *105*, 4734-4739.
12. (a) Mehta, G.; Padma, S. In *Carbocyclic Cage Compounds: Chemistry and Applications*; Ösawa, E.; Yonemitsu, O., Ed.; VCH: Weinheim, Germany, 1922; pp 183-215. (b) Mehta, G. In *Strain and Its Implications in Organic Chemistry*; de Meijere, A., Blechert, S., Ed.; Kluwer Academic Publishers: Boston, 1988; pp 269-281. (c) Nogita, R.; Matohara, K.;

Yamaji, M.; Oda, T.; Sakamoto, Y.; Kumagai, T.; Lim, C.; Yasutake, M.; Shimo, T.; Jefford, C. W.; Shinmyozu, T. *J. Am. Chem. Soc.* **2004**, *126*, 13732 -13741. (d) Chou, T.-C.; Lin, G.-H.; Yeh, Y.-L.; Lin, K.-J. *J. Chin. Chem. Soc.* **1997**, *44*, 477-493. (e) Chou, T.-C.; Yeh, Y.-L.; Lin, G.-H. *Tetrahedron Lett.* **1996**, *37*, 8779-8782. (f) Mehta, G.; Padma, S. *Tetrahedron* **1991**,*47*, 7783-7806. (g) Forman, M. A.; Dailey, W. P. *Org. Prep. & Proc. Int.* **1994**, *26*, 291-320.

13. (a) Mitsunobu, O.; Yamada, M. *Bull. Chem. Soc. Jpn.,* **1967**, *40*, 2380. (b) Nicolaou, K. C.; Boddy, C. N. C.; Natarajan, S.; Yue, T.-Y.; Li, H.; Bräse, S.; Ramanjulu, J. M. *J. Am. Chem. Soc.,* **1997**, *119*, 3421-3422.
14. In our experiment using rose bengal as sensitizer, an 1,3-diepoxide product resulting from the rearrangement of endoperoxide was isolated in various yields depending on the reaction temperature.
15. No noticeable reaction occurred when performed in solution (toluene or xylene). In the absence of $CaCO_3$, the yields were low, ranging from 10% to 30%.
16. (a) Marchand, A. P. *Stereochemical Applications of NMR Studies in Rigid Bicyclic Systems*; Verlag Chemie International: New York, 1982. (b) Grimme, W.; Gossel, J.; Lex, J. *Angew. Chem. Int. Ed.* **1998**, *37*, 473-475. (c) Grimme, W.; Wortmann, J.; Frowein, D.; Lex, J.; Chen, G.; Gleiter, R. *J. Chem. Soc., Perkin Trans. 2*, **1998**, 1893-1900. (d) Astin, K. B.; Mackenzie, K. *J. Chem. Soc., Perkin Trans. 2* **1975**, 1004-1010.
17. (a) Lin, C.-T.; Chen, K.-Z; Chou, T.-C. *Tetrahedron*. **2003**, *59*, 1493-1500. (b) Lin, C.-T.; Hsu, H.-C.; Wang, M.-F., Chou, T.-C. *Tetrahedron*. **2000**, *56*, 5383-5390. (c) Lin, C.-T.; Hsu, H.-C.; Chou, T.-C. *J. Org. Chem.* **1999**, *64*, 7260-7264. (d) Chou, T.-C.; Jiang, T. S.; Hwang, J.-T.; Lin, K.-J.; Lin, C.-T. *J. Org. Chem.* **1999**, *64*, 4874-4883.
18. The diacetate and dimethoxy derivatives of diol **6** were reported to be inactive in the Diels-Alder reaction with TDCp (see ref. 9).
19. Saravanan, P.; Chandrasekhar, M.; Anand, R. V.; Singh, V. K. *Tetrahedron Lett*. **1998**, *39*, 3091-3092.
20. Eaton, P. E.; Patterson, D. R. *J. Am. Chem. Soc.* **1978**, *100*, 2573-2575.
21. Sheldrick, G. M. SHLXS97—A Program for Automatic Solution of Crystal Structures; University of Göttingen: Germany, 1997.
22. Sheldrick, G. M. SHLXL97—A Program for Automatic Refinement of Crystal Structures; University of Göttingen: Germany, 1997.