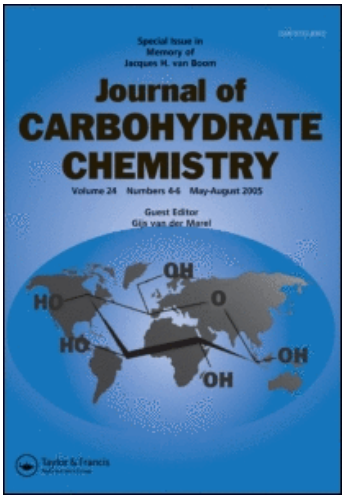

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Inter- and Intramolecular Diels-Alder Cycloaddition of Enantiopure 4,5-*O*, *C*-Functionalized Cyclohex-2-Enone and Its Derivatives Prepared from D-Glucose

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INTER- AND INTRAMOLECULAR DIELS-ALDER CYCLOADDITION OF ENANTIOPURE 4,5-*O*, *C*-FUNCTIONALIZED CYCLOHEX-2-ENONE AND ITS DERIVATIVES PREPARED FROM D-GLUCOSE[1]

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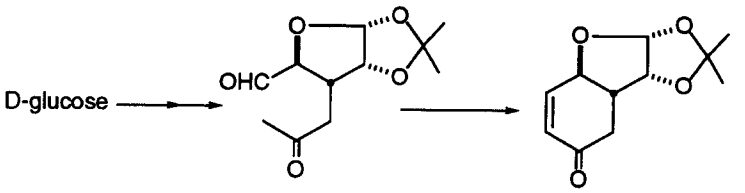
ABSTRACT

The Lewis acid catalyzed reaction of a D-glucose derived functionalized cyclohex-2-enone **1** with furan provided the 1,4-conjugate adducts **3** and **4**. On the other hand, thermal intermolecular Diels-Alder cycloaddition of **1** with 1,3-cyclohexadiene provided two *endo*-cycloadducts **5** and **6** in a good combined yield. The intramolecular cycloaddition of sorbic acid ester **20** of the allylic alcohol **19**, prepared from **1**, proceeded under thermal conditions to give a mixture of highly functionalized decalin derivatives **21-23**, whose stereostructures were determined by chemical modification.

INTRODUCTION

Previously, we reported a practical preparation of a 4,5-*O*,*C*-functionalized cyclohex-2-enone **1** employing an intramolecular aldol condensation of the D-glucose-derived substrate as the key carbocyclization step.[2] We have also demonstrated the utility of **1** as an enantiopure building block for natural products synthesis such as the bisabolene-type sesquiterpene paniculide B.[3] Compound **1** was also converted into stereoisomers of



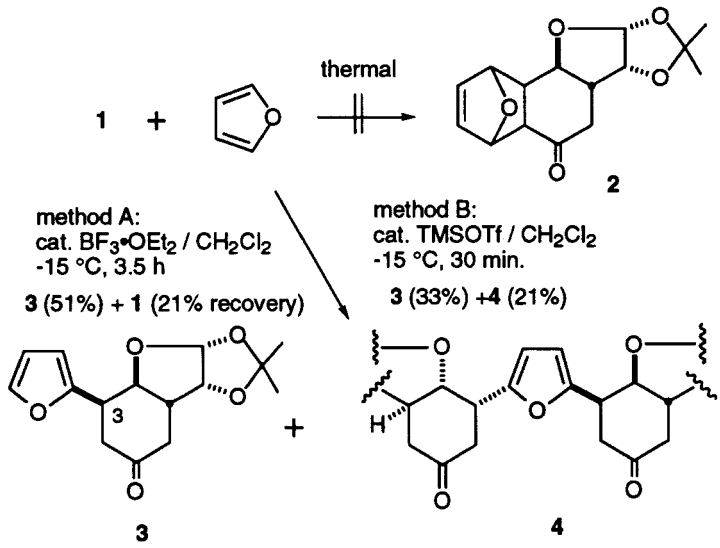
1

carba-sugars and carba-aminosugars.[2,4] For an extension of our ongoing synthetic efforts on the preparation of versatile and enantiopure carbocycles,[5] we explored a series of Diels-Alder cycloadditions of **1** and its derivatives, and some results are described herein.

RESULTS AND DISCUSSION

First, we investigated the intermolecular cycloaddition of **1** with furan under thermal or Lewis acid catalyzed conditions. The expected Diels-Alder cycloaddition leading to the cycloadduct(s) **2** did not take place under several thermal conditions with excess furan, i.e., (1) under reflux (neat) in the presence of a catalytic amount of hydroquinone, (2) under reflux in toluene, or (3) by heating at 130 °C or 200 °C in toluene (Scheme 1). On the other hand, when a mixture of **1** and furan in CH_2Cl_2 was treated with $BF_3 \cdot OEt_2$ (10 mol% of **1**) at -15 °C, the (formal) 1,4-conjugate adduct **3** was obtained stereoselectively in 51% yield (21% of **1** was recovered). The configuration at C3 in **3** was determined by its ^1H NMR analysis. Under these Lewis acid catalyzed conditions, the expected cycloaddition did not proceed,[6] however, the nucleophilic attack of furan on the β-carbon of the enone **1** proceeded exclusively from the *Re* -face of the cyclohexenone ring. It is most likely that the resulting dihydrofuran intermediate aromatized rapidly to form **3**. However, another pathway[7] via a fragmentation of the initially formed Diels-Alder adduct can not be excluded. Interestingly, when a catalytic amount of trimethylsilyl trifluoromethanesulfonate (10% mol) was used as a Lewis acid at -15 °C, the 2,5-doubly substituted furan **4** was obtained in 21% yield along with 33% yield of **3**. The C_2 symmetrical structure of **4** was confirmed based on the ^1H NMR and mass spectral analysis. Some other Lewis acids were also examined for the reaction of **1** and furan, however, none of which gave the cycloadduct(s).[8]

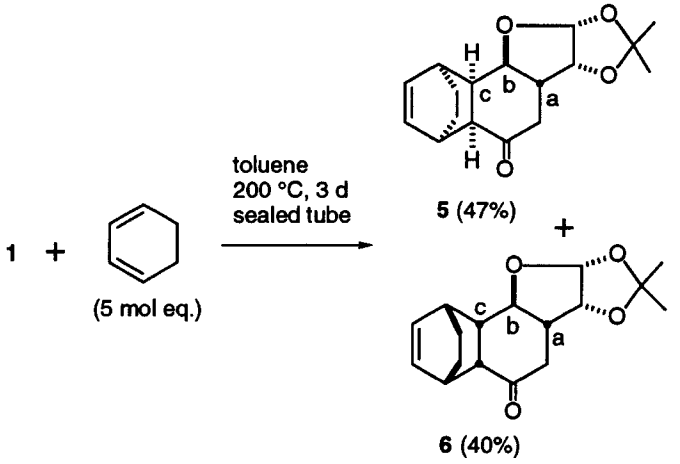
Next, the cycloaddition of **1** with 1,3-cyclohexadiene was explored. We found eventually that thermal conditions were solely effective for the desired Diels-Alder cycloaddition, but typical Lewis acids did not mediate the cycloaddition.[9] When a solution of **1** and 1,3-cyclohexadiene in toluene was heated at 200 °C in a sealed tube for 3 days, two cycloadducts **5** and **6** were isolated in 47% and 40% yields, respectively,



Scheme 1

after chromatographic separation on SiO_2 (Scheme 2).[10] The cycloaddition did not occur below 200 °C, and **1** was recovered intact. Stereochemical assignment of the ring juncture (H_c) for the cycloadducts **5** and **6** was achieved based on their ^1H NMR analysis. In the ^1H NMR of **5**, H_b appeared as a doublet of doublets with $J_{a,b}$=11.4 Hz and $J_{b,c}$= 5.5 Hz, respectively. On the other hand, H_b of **6** appeared as a triplet with $J_{a,b}$=$J_{b,c}$ =11.1 Hz.

The whole structure determination of **5** and **6** was achieved after the following chemical transformations. $NaBH_4$ reduction of **5** followed by acetylation of the resulting β-hydroxy derivative **7** gave the acetate **8** (Scheme 3). The hydride delivery to the carbonyl in **5** occurred exclusively from the α-side of the cyclohexanone ring. Ozonolysis of the bridged double bond in **8** followed by reductive work-up, $NaBH_4$ reduction provided the decalin derivative **9**. Examination of the ^1H NMR of **9** verified the stereochemistries of H_d and H_e ($J_{d,e}$= 2.9 Hz). The stereochemistry of the bridged head in **5** was determined as follows. A reaction sequence from **8**, i.e., acid hydrolysis, $NaIO_4$ oxidation of the resulting hemiacetal **10**, $NaBH_4$ reduction followed by acetylation of the resulting diol **11** provided triacetate **12**. In the NOE difference measurements of **12**, 5.3% enhancement of one of the vinyl protons was observed when one of the methylene protons was irradiated.

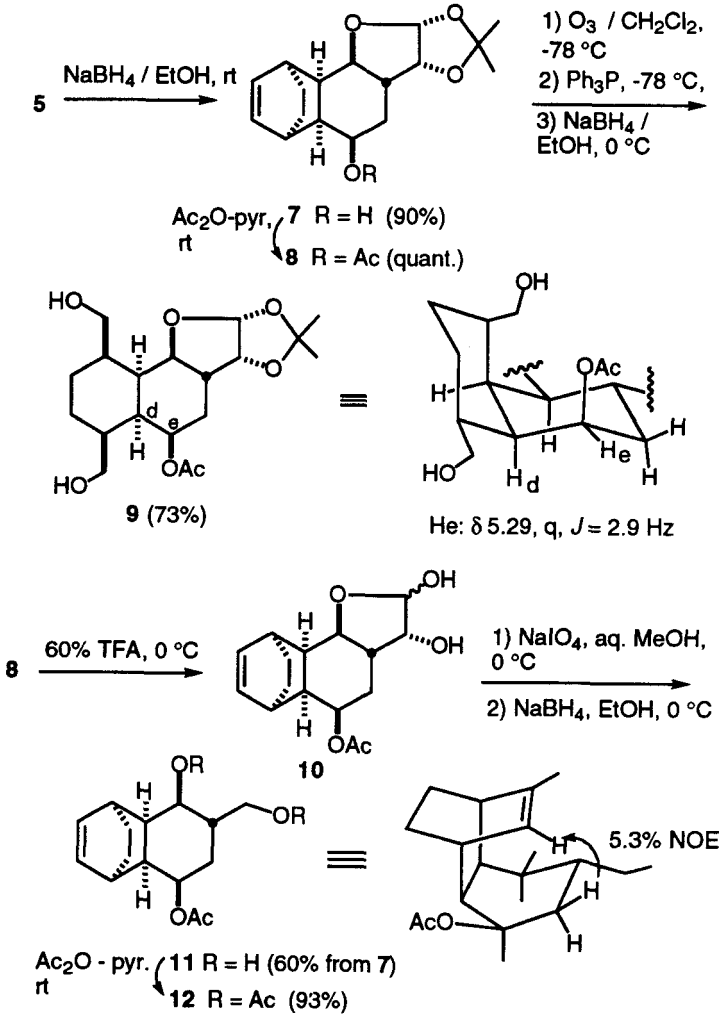


Scheme 2

Employing the same functional group transformations applied for **5**, the other cycloadduct **6** was converted into two derivatives **15** via **13** and **14**, and **18** via **16** and **17** (Scheme 4). The coupling constant ($J_{d,e}$=6.0 Hz) in **15** and NOE measurements of **18** verified their structures, therefore that of **6**. The Diels-Alder cycloaddition of **1** with 1,3-cyclohexadiene provided two *endo*-adducts **5** and **6** in a high combined yield but without meaningful π–facial stereoselectivity.

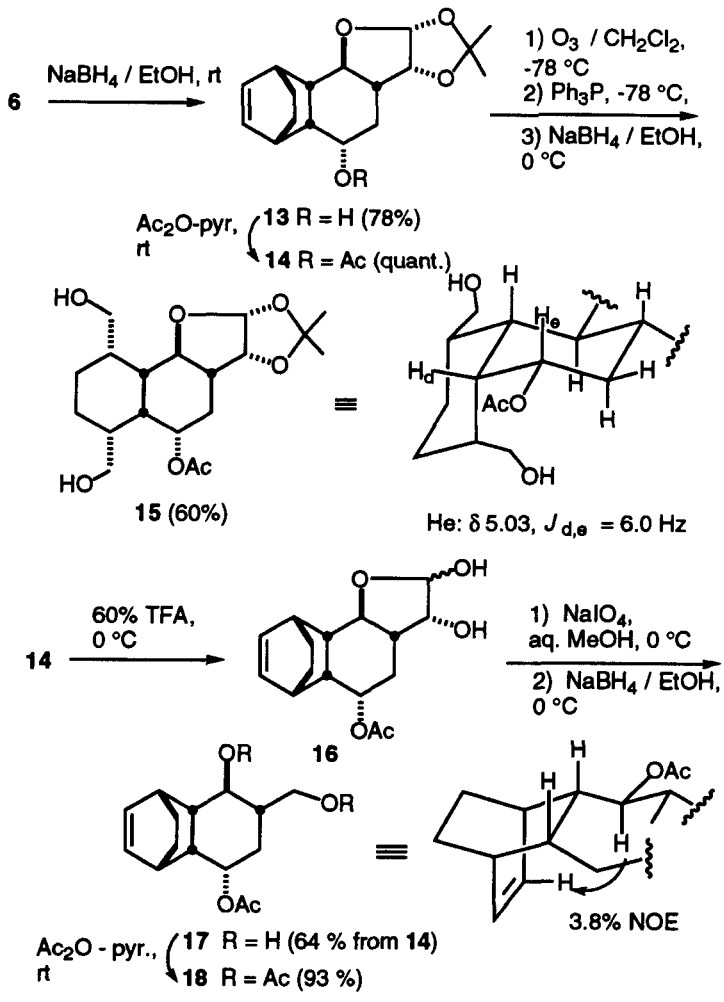
Next, we explored the intramolecular cycloaddition of trienoic ester **20** prepared from **1**. Luche reduction[11] of **1** proceeded stereoselectively to give previously reported α-allylic alcohol **19**,[4] contaminated by a trace amount of the β-allylic alcohol (not shown) (Scheme 5).[12] Esterification of **19** with (*E*,*E*)-2,4-hexadienoic acid (sorbic acid) gave the substrate **20**. Although Lewis acids did not effect the intramolecular Diels-Alder cycloaddition of **20**, three cycloaddition products **21**-**23** were obtained when **20** was heated in *o*-xylene at 200 °C (in a sealed tube) for several hours. One cycloadduct **23** (6%) could be cleanly separated by chromatography of the reaction mixture on SiO_2, however, other products **21** and **22** (26% combined yield) were obtained as an inseparable mixture (56% of **20** was recovered).[13]

The inseparable mixture of **21** and **22** (ca. 7:1 based on the ^1H NMR analysis) was converted into dibenzoates **24** and **25** by a three-step sequence. Compounds **24** and **25** were cleanly separated by chromatography on SiO_2 in 67% and 10% yields, respectively (Scheme 6). The ^1H NMR analysis including NOE measurements of **24** and **25** unambiguously verified their structures. On the other hand, the product **23** was



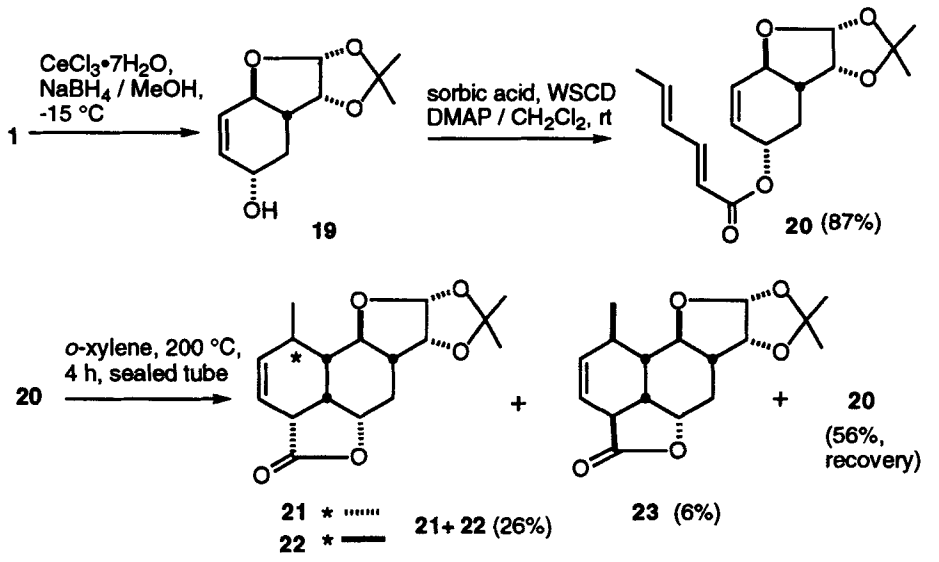
Scheme 3

converted into diol **26** by Dibal-H followed by $NaBH_4$ reduction. The ^1H NMR analysis of **26** unambiguously verified the whole structure of **26**, therefore that of **23**. From these results, the ratio of the cycloadducts **21-23** was estimated to be 6.6:1:1.8. As anticipated, the intramolecular Diels-Alder cycloaddition of **20** took place with complete π-facial selection, i.e., by attack of the diene part to the α-side of the cyclohexene ring. Surprisingly, the presence of the cycloadduct **22** raised a question whether the cycloaddition proceeded only via a concerted mechanism which leads to **21** and/or **23** but



Scheme 4

not to **22**. We suspected the possibility of epimerization at the α-carbon of the lactone carbonyl in **21**-**23**. Therefore, we examined the thermal stability of the cycloadducts **21**-**23**. The mixture (ca. 7:1) of **21** and **22** showed no change of the diastereomeric ratio after heating (at 200 °C for 5 h). On the contrary, the diastereomer **23** was substantially epimerized to **22** under the thermal conditions. The diastereomeric ratio of **22** and **23** reached to 1.9 : 1 after heating **23** at 200 °C for 14 h. From this evidence, we concluded that the cycloadduct **22** was formed from the initially formed **23** through the epimerization at the α-carbon of the lactone carbonyl group. Taking this epimerization into consideration, the ratio of the initially formed **21** and **23** was estimated to be

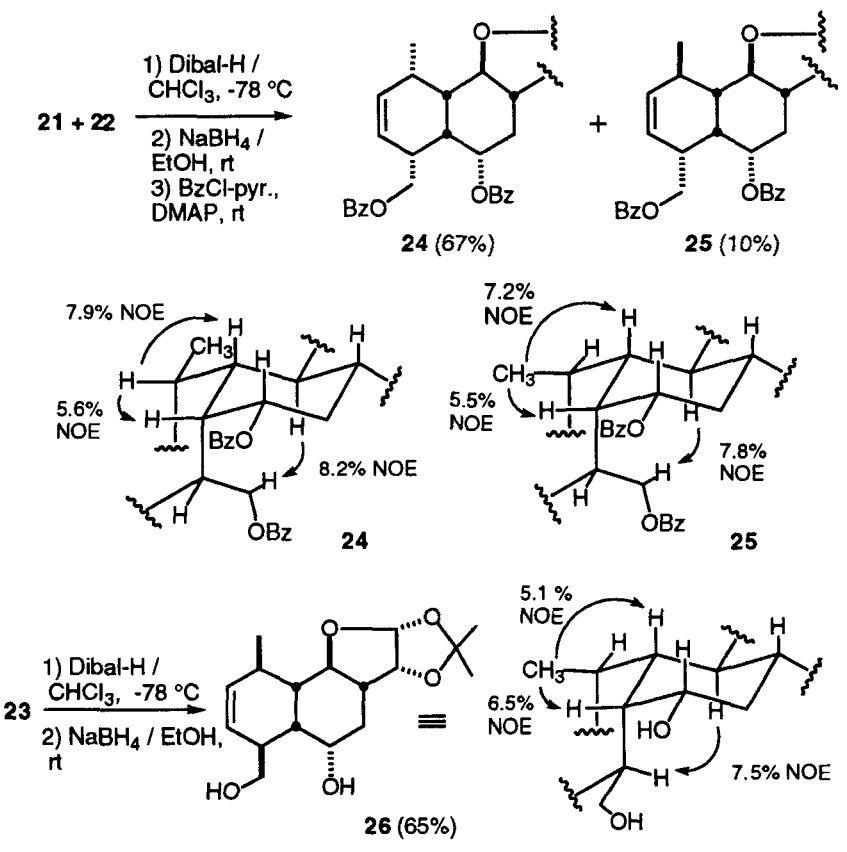


Scheme 5

approximately 6.6:2.8. Consequently, the intramolecular Diels-Alder cycloaddition of **20** proceeded with a marginal *endo-exo* stereoselectivity. In connection with our present studies, Boeckman's group previously reported the intramolecular Diels-Alder cycloadditions of the structurally similar substrates, i.e., acyclic trienes derived from coupling of sorbic acid and ethyl 4-bromocrotonate or methyl 2-(bromomethyl)acrylate.[14] The thermal intramolecular Diels-Alder cycloaddition of the triene obtained from the former coupling reaction provided a 9:1 mixture of *trans*- and *cis*-fused 8-oxabicyclo[4.3.0]non-2-en-9-one system. They argued the role of the ester carbonyl attached to the diene units in the transition states of the cycloadditions. In our case, we have no firm reason to explain the stereochemical bias observed in the cycloaddition of **20**, i.e., the ratio of the initially formed *cis*- and *trans*-fused γ-butyrolactones **21** and **23** = ca. 7:3. Although further experimental evidence should be accumulated for the precise account for the stereochemical outcome of the cycloadditions, the present results imply an access to the *cis*-fused decalin frameworks carrying diverse *O*- and *C*-functionalities.

EXPERIMENTAL

General methods. Melting points are uncorrected. Specific rotations were measured in a 10-mm cell. ^{1}H NMR spectra were recorded at 270 MHz in $CDCl_3$



Scheme 6

solution with tetramethylsilane as an internal standard. ^{13}C NMR spectra were recorded at 100 MHz in $CDCl_3$ solution. Thin-layer chromatography (TLC) was performed with a glass plate coated with Kieselgel 60 GF_{254} (Merck). Crude reaction mixtures and extractive materials were purified by chromatography on silica gel 60 K070 (Katayama Chemicals).

Unless otherwise specified, reactions were carried out at room temperature (rt). Organic extracts were dried over anhydrous Na_2SO_4. Reagents and solvents were removed by concentration in vacuo using an evaporator at 35-45 °C. Solvents were dried (drying reagent in parenthesis) and distilled prior to use: tetrahydrofuran=THF ($LiAlH_4$, then Na/benzophenone ketyl), *N,N*-dimethylformamide=DMF ($MgSO_4$), CH_2Cl_2 (CaH_2), benzene (CaH_2), dimethyl sulfoxide= DMSO (CaH_2), pyridine (NaOH), and toluene (CaH_2).

BF_3•OEt_2 Catalyzed Addition of Furan to 1: Formation of the 1,4-Conjugate Adduct 3. The following reaction was carried out under Ar. To a cold (-15 °C) stirred solution of **1** (486 mg, 2.3 mmol) in CH_2Cl_2 (10 mL) were added BF_3•OEt_2 (28.5 μL, 0.23 mmol) and then furan (10 mL). After stirring at -15 °C for 3.5 h, the reaction was quenched with H_2O (2 mL), diluted with saturated aq $NaHCO_3$ (100 mL), and extracted with CH_2Cl_2 (50 mL x3). The combined extracts were dried and concentrated in vacuo. The residue was purified by column chromatography on silica gel (acetone/toluene, 1:40) to give **3** (263 mg), a mixture of **1** and **3** (170 mg), and 73 mg (15%) of **1** was recovered. The mixture of **1** and **3** (170 mg) was subjected to the repeated reaction conditions using 5 μL of BF_3•OEt_2, 1.8 mL of furan in 2 mL of CH_2Cl_2 at -15 °C for 3 h. After chromatographic separation, 65 mg of **3**, 47 mg of the mixture of **1** and **3**, and 29.5 mg of recovered **1** were obtained. After this one-recycling, 328 mg (51%) of **3** was obtained. **3** as colorless crystals, mp 155-156 °C; TLC, R_f 0.44 (acetone/toluene, 1:5); $[\alpha]^{26}_D$ -21.6° (*c* 1.02, $CHCl_3$); IR (neat) 1720 cm^{-1}; ^1H NMR δ 1.33, 1.58 (2s, 3 H x 2), 1.93-2.05 (m, 1 H), 2.61- 2.81 (m, 4 H), 3.83-3.88 (m, 1 H), 4.33 (dd, *J* =4.8, 11.0 Hz, 1 H), 4.49 (t, *J* =3.7 Hz, 1 H), 5.82 (d, *J* =3.7 Hz, 1 H), 6.14 (dd, *J* = 0.7, 3.3 Hz, 1 H), 6.31 (dd, *J* = 1.8, 3.3 Hz, 1H), 7.36 (dd, *J* = 0.7, 1.8 Hz, 1 H);^{13}C NMR δ 26.0, 26.3, 35.7, 39.4, 42.18, 42.23, 78.1, 79.3, 106.7, 108.5, 110.2, 111.9, 142.3, 152.5, 207.8.

Anal. Calcd for $C_{15}H_{18}O_5$: C, 64.73; H, 6.52. Found: C, 64.49, H, 6.71.

TMSOTf Catalyzed Addition of Furan to 1: Formation of the Bis-1,4-Conjugate Adduct 4. The following reaction was carried out under Ar. To a cold (-15 °C) stirred solution of **1** (51 mg, 0.25 mmol) in CH_2Cl_2 (1 mL) were added TMSOTf (5 μL, 0.024 mmol) and furan (16 μL). After stirring at -15 °C for 30 min, the reaction was quenched with H_2O (1 mL), diluted with saturated aq $NaHCO_3$ (20 mL), extracted with CH_2Cl_2 (10 mL x 3). The combined extracts were dried and concentrated in vacuo. The residue was purified by column chromatography on silica gel (EtOAc/hexane, 1:4 to 1:2) to give **3** (23 mg, 33%) and **4** (25 mg, 21%). **4** as colorless crystals, mp 264.5-265.0 °C; TLC, R_f 0.21 (acetone/toluene, 1:5); $[\alpha]^{19}_D$ -67.3° (*c* 0.91, $CHCl_3$); IR ($CHCl_3$) 1716 cm^{-1}; ^1H NMR δ 1.34, 1.57 (2s, 6 H x 2), 2.09-2.21 (m, 2 H), 2.49-2.76 (m, 8 H), 3.73-3.77 (m, 2 H), 4.27 (dd, *J* =4.8, 11.4 Hz, 2 H), 4.59 (t, *J* =3.9 Hz, 2 H), 5.76 (d, *J* =3.9 Hz, 2 H), 6.08 (s, 2 H); ^{13}C NMR δ 26.0, 26.2, 35.9, 39.2, 42.6, 42.8, 77.8, 79.4, 106.6, 109.4, 111.9, 152.5, 207.5; MS *m/z* 489 (M+H), 474 (M+H-CH_3).

Diels-Alder Cycloaddition of 1 with 1,3-Cyclohexadiene: Formation of the *endo*-Cycloadducts 5 and 6. Compound **1** (200 mg, 0.95 mmol) and 1,3-cyclohexadiene (0.54 mL, 5.7 mmol) were dissolved in toluene (4 mL) and the solution was transferred to a 10 mL Pyrex sealed tube with a screwed stopper. The tube was

purged with Ar. A total of five sealed tubes, each with the same content, were prepared, and all were heated at 200 °C for 24 h. Then, 0.54 mL of 1,3-cyclohexadiene was added to each sealed tube. The sealed tubes were heated at 200 °C for an additional 48 h. The reaction solutions were combined and concentrated in vacuo. The residue was purified by column chromatography on silica gel (EtOAc/hexane, 1:10 to 1:6) to give **5** (648 mg, 47%) and **6** (549 mg, 40%).

5 as colorless crystals, mp 139.0-139.5 °C: TLC, Rf 0.47 (EtOAc/hexane, 1:4); $[\alpha]^{28}_D$ + 59.0 ° (*c* 0.99, $CHCl_3$); IR ($CHCl_3$) 1694 cm^{-1}; ^1H NMR δ 1.32, 1.49 (2s, 3 H x 2), 1.16-1.38, 1.54-1.67 (2m, 2 H x 2), 2.09-2.21 (m, 1 H), 2.34-2.38, 2.57-2.64 (2m, 2 H x 2), 2.93-2.95 (m, 1 H), 3.10-3.12 (m, 1 H), 4.02 (dd, *J* =5.5, 11.4 Hz, 1 H), 4.49 (t, *J* =3.9 Hz, 1 H), 5.91 (d, *J* =3.9 Hz, 1 H), 6.14 (td, *J* =7.1, 1.1 Hz, 1 H), 6.32 (t, *J* =7.1 Hz, 1 H); ^{13}C NMR δ 23.0, 26.0, 26.2, 27.3, 28.6, 35.6, 37.5, 38.9, 39.2, 53.0, 78.0, 79.5, 106.2, 111.6, 132.5, 136.0, 213.1.

Anal. Calcd for $C_{17}H_{22}O_4$: C, 70.32; H, 7.64. Found: C, 69.95, H, 7.83.

6 as colorless crystals, mp 95.5-96.0 °C: TLC, Rf 0.28 (EtOAc/hexane, 1:4); $[\alpha]^{24}_D$ -91.9 ° (*c* 1.07, $CHCl_3$); IR (neat) 1700 cm^{-1}; ^1H NMR δ 1.31, 1.46 (2s, 3 H x 2), 1.23-1.60 (m, 4 H), 2.12 (ddd, *J* = 4.2, 7.2, 11.1 Hz, 1 H), 2.39 (dd, *J* = 11.1, 19.0 Hz, 1 H), 2.50 (dd, *J* = 7.2, 19.0 Hz, 1 H), 2.39-2.45 (m, 1 H), 2.61 (dd, *J* = 2.6, 11.0 Hz, 1 H), 2.81-2.83 (m, 1 H), 3.14-3.17 (m, 1 H), 3.33 (t, *J* = 11.1 Hz, 1 H), 4.57 (t, *J* = 4.2 Hz, 1 H), 5.92 (d, *J* = 4.2 Hz, 1 H), 6.17 (t, *J* = 7.3 Hz, 1 H), 6.31 (td, *J* = 1.3, 7.3 Hz, 1 H); ^{13}C NMR δ 23.3, 25.2, 26.1, 26.4, 30.5, 32.0, 36.4, 42.8, 45.2, 52.5, 79.6, 80.1, 106.9, 111.9, 132.5, 135.3, 211.2.

Anal. Calcd for $C_{17}H_{22}O_4$: C, 70.32; H, 7.64. Found: C, 70.03, H, 7.85.

$NaBH_4$ Reduction of 5 Followed by Acetylation: Formation of 8 via 7. To a cold (0 °C) stirred solution of **5** (109 mg, 0.37 mmol) in EtOH (2 mL) was added $NaBH_4$ (14 mg, 0.37 mmol). The solution was stirred for 5 h, and $NaBH_4$ (14 mg) was added. The solution was stirred for an additional 2 h, neutralized with Amberlite IR-120 [H^+]. The resin was removed by filtration and washed with MeOH. The combined filtrate and washing were concentrated in vacuo. The residue was purified by column chromatography on silica gel (AcOEt/hexane, 1:4) to give **7** (98 mg, 90%) as colorless crystals, mp 150.0-151.0 °C: TLC, Rf 0.22 (EtOAc/hexane, 1:2); $[\alpha]^{23}_D$ +20.9° (*c* 0.99, $CHCl_3$); IR ($CHCl_3$) 3609 cm^{-1}; ^1H NMR δ 1.31, 1.48 (2s, 3 H x 2), 1.23-1.38 (2m, total 5 H), 1.88-2.11 (m, 2 H), 2.36, 2.53 (2ddd, each *J* = 1.9, 6.3, 10.8 Hz, 1 H x 2), 2.74-2.76, 2.87-2.90 (2m, 1 H x 2), 3.99 (dd, *J* = 6.3, 12.0 Hz, 1 H), 4.09 (dt, *J* = 11.0, 6.3 Hz, 1 H), 4.40 (t, *J* = 3.8 Hz, 1 H), 5.76 (d, *J* = 3.8 Hz, 1 H), 6.16-6.25 (m, 2 H).

Anal. Calcd for $C_{17}H_{24}O_4$: C, 69.84; H, 8.27. Found: C, 69.57, H, 8.23.

Compound **7** (75 mg, 0.26 mmol) was acetylated with acetic anhydride (1 mL) in pyridine (1 mL) for 4 h. The solution was concentrated in vacuo. The residue was purified by column chromatography on silica gel (EtOAc/hexane, 1:8) to give **8** (88.5 mg, quant.) as a colorless oil: TLC, R_f 0. 59 (EtOAc/hexane, 1:2); $[\alpha]^{23}_D$ +37.5 ° (*c* 1.12, $CHCl_3$); IR (neat) 1750 cm^{-1}; ^1H NMR δ 1.30, 1.49 (2s, 3 H x 2), 1.21-1.27, 1.42-1.52 (2m, total 5 H), 1.90-2.06 (m, 2 H), 2.07 (s, 3 H), 2.52-2.55 (m, 2 H), 2.65-2.67, 2.75-2.77 (2m, 1 H x 2), 3.98-4.04 (m, 1 H), 4.40 (t, *J* = 3.5 Hz, 1 H), 5.03-5.12 (m, 1 H), 5.76 (d, *J* = 3.5 Hz, 1 H), 6.16-6.27 (m, 2 H).

Conversion of 8 into 9. To a cold (-78 °C) solution of **8** (23 mg, 0.069 mmol) in CH_2Cl_2 (1 mL) was bubbled ozone (ca. 3% in O_2) for 20 min. To the solution was added Ph_3P (27 mg, 0.10 mmol) at -78 °C, and the solution was stirred at -78 °C for 15 min, then gradually warmed to rt. The solvent was removed by evaporation. The residue was dissolved in EtOH (1 mL), and 5 mg (0.14 mmol) of $NaBH_4$ was added at 0 °C. After 30 min and 60 min, 5 mg of $NaBH_4$ was added, and the solution was stirred at 0 °C totally for 1.5 h. The mixture was neutralized with Amberlite IR-120 [H^+]. The resin was removed by filtration, and washed with MeOH. The combined filtrate and washing were concentrated in vacuo. The residue was purified by column chromatography on silica gel (acetone/toluene, 1:5 to 1:3) to give **9** (19 mg, 73%) as a colorless oil: TLC, R_f 0.50 (acetone/toluene, 1:1); $[\alpha]^{29}_D$ -58.9° (*c* 0.75, $CHCl_3$); IR (neat) 3480, 1730 cm^{-1}; ^1H NMR δ 1.35, 1.53 (2s, 3 H x 2), 1.38-1.84, 1.99-2.17, 2.26-2.33 (4m, total 7 H), 2,08 (s, 3 H), 2.83-2.92, 3.51-3.65 (2m, 2 H x 2), 4.08 (dd, *J* = 7.0, 12.1 Hz, 1 H), 4.62 (t, *J* = 3.8 Hz, 1 H), 5.29 (q, *J* = 2.9 Hz, 1 H), 5.90 (d, *J* = 3.8 Hz, 1 H); ^{13}C NMR δ 21.6, 21.8, 25.8, 25.9, 27.8, 28.4, 36.8, 38.1, 38.3, 38.8, 41.4, 64.6, 67.6, 78.9, 79.8, 105.3, 112.7, 170.7, 173.6.

Conversion of 8 into Diol 11. A solution of **8** (62 mg, 0.19 mmol) in 60% aqueous CF_3COOH (1.2 mL) was stirred at 0 °C for 6 h, and neutralized with 1.0 M aqueous NaOH solution. This was diluted with saturated brine (20 mL) and extracted with CH_2Cl_2 (10 mL x 3). The combined extracts were dried and concentrated in vacuo to give crude hemiacetal **10** as a colorless oil, which was used for next step.

The crude **10** was dissolved in MeOH (1 mL) and an aqueous solution (1 mL) of $NaIO_4$ (59 mg, 0.26 mmol) was added. After stirring for 20 min, the solution was diluted with saturated brine (20 mL), and extracted with CH_2Cl_2 (10 mL x 3). The combined extracts were dried and concentrated in vacuo. The residue was dissolved in EtOH (1 mL) and $NaBH_4$ (14 mg, 0.37 mmol) was added. After stirring for 80 min, the solution was neutralized with Amberlite IR-120 [H^+]. The resin was removed by filtration, and washed with MeOH. The combined filtrate and washing were concentrated in vacuo.

The residue was purified by column chromatography on silica gel (acetone/toluene, 1:8 to 1:5) to give **11** (29.5 mg, 60%) as a colorless oil: TLC, R_f 0.38 (acetone/toluene, 1:2); $[\alpha]^{26}_D$ +7.7° (*c* 0.99, $CHCl_3$); IR (neat) 3400, 1740 cm^{-1}; ^1H NMR δ 1.15 (ddd, *J* = 2.9, 5.4, 13.2 Hz, 1 H), 1.24-1.28, 1.44-1.54 (2m, 2 H x 2), 1.73 (dt, *J* = 11.4, 13.2 Hz, 1 H), 1.81-1.93 (m, 1 H), 2.05 (s, 3 H), 2.29-2.42, 2.64-2.68, 2.88-2.92 (3m, 2 H, 1 H, 1H), 3.59-3.63 (m, 2 H), 3.96 (dd, *J* = 5.1, 9.2 Hz, 1 H), 5.02 (dt, *J* = 11.4, 5.4 Hz, 1 H), 6.22, 6.28 (each ddd, each *J* = 1.6, 6.7, 8.1 Hz, 1 H x 2);^{13}C NMR δ 21.4, 25.7, 25.8, 27.0, 29.3, 30.0, 37.9, 42.0, 44.9, 68.6, 69.3, 71.2, 131.8, 132.5, 170.5; HRMS, calcd for $C_{15}H_{22}O_4$ (M^+) *m/z* 266.1516, found 266.1498.

Acetylation of 11. Compound **11** (17 mg, 0.064 mmol) was acetylated with acetic anhydride (1 mL) in pyridine (1 mL) for 2.5 h, and the mixture was concentrated in vacuo. The residue was purified by column chromatography on silica gel (EtOAc/hexane, 1:5) to give **12** (21 mg, 93%) as a colorless oil, which gradually crystallized on standing at 0 °C, mp 78.5-79.0 °C: TLC, R_f 0.27 (EtOAc/hexane, 1:3); $[\alpha]^{22}_D$ -39.3° (*c* 1.04, $CHCl_3$); IR (neat) 1735 cm^{-1}; ^1H NMR δ 1.22-1.28 (m, 2 H), 1.45-1.49 (m, 2 H), 1.56-1.65 (m, 1 H), 1.77 (q, *J* = 12.5 Hz, 1 H), 1.99-2.13 (m, 1 H), 2.06, 2.08 (2s, 6 H, 3 H), 2.44-2.64 (2ddd, each *J* = 2.1, 6.1, 10.8 Hz, 1 H x 2), 2.62-2.64, 2.70-2.72 (2m, 1 H x 2), 3.89 (dd, *J* = 3.7, 11.0 Hz, 1 H), 3.95 (dd, *J* = 4.8, 11.0 Hz, 1 H), 4.99-5.10 (m, 2 H), 6.21-6.33 (m, 2 H); ^{13}C NMR (100 Hz) δ 20.8, 21.1, 21.2, 25.45, 25.52, 27.7, 29.5, 33.7, 41.2, 41.8, 65.6, 68.5, 69.1, 131.6, 132.7, 170.2, 170.3, 171.3.

Anal. Calcd for $C_{19}H_{26}O_6$: C, 65.13; H, 7.48. Found: C, 64.86, H, 7.74.

$NaBH_4$ Reduction of 6 Followed by Acetylation: Formation of 14 via 13. As analogously described in the preparation of **7**, compond **6** (142 mg, 0.49 mmol) was converted into **13** (111 mg, 78%) with $NaBH_4$ (37 mg) in EtOH. In this reduction, the β-hydroxy derivative (16 mg) was also obtained in 11% yield after chromatographic separation of the reaction mixture. **13** as white crystals, mp 106.0-106.5 °C: TLC, R_f 0.43 (EtOAc/hexane, 1:2); $[\alpha]^{23}_D$ +38.2° (*c* 1.00, $CHCl_3$); IR ($CHCl_3$) 3520 cm^{-1}; ^1H NMR δ 1.32, 1.50 (2s, 3 H x 2), 1.26-1.29, 1.53-1.61 (2m, total 4 H), 1.89-2.04 (m, 4 H), 2.18 (ddd, *J* = 2.2, 3.5, 10.8 Hz, 1 H), 2.62-2.67, 2.82-2.86 (2m, 1 H x 2), 3.97 (t, *J* = 11.0 Hz, 1 H), 4.01-4.06 (m, 1 H), 4.50 (t, *J* = 3.9 Hz, 1 H), 5.83 (d, *J* = 3.9 Hz, 1 H), 6.37-6.44 (m, 2 H); HRMS, calcd for $C_{17}H_{24}O_4$ (M^+) *m/z* 292.1673, found 292.1692.

Compound **13** (86.5 mg, 0.30 mmol) was acetylated with acetic anhydride (1 mL) in pyridine (1 mL) for 23 h. After chromatographic purification of the reaction mixture on silica gel (EtOAc/hexane, 1:4), **14** (103 mg, quant.) was obtained as a colorless oil: TLC, R_f 0. 57 (EtOAc/hexane, 1:2); $[\alpha]^{24}_D$ +21.1 ° (*c* 0.97, $CHCl_3$); IR (neat) 1740 cm^{-1}; ^1H NMR δ 1.30, 1.48 (2s, 3 H x 2), 1.24-1.29, 1.49-1.61 (2m, total 5 H), 1.83 (ddd, *J*

= 1.5, 9.4, 15.4 Hz, 1 H), 1.91-2.07 (m, 2 H), 1.99 (s, 3 H), 2.23 (ddd, J = 2.0, 4.5, 10.9 Hz, 1 H), 2.47-2.51, 2.76-2.79 (2m, 1 H x 2), 3.87 (t, J = 10.9 Hz, 1 H), 4.47 (t, J = 3.9 Hz, 1 H), 5.17 (td, J = 4.5, 1.5 Hz, 1 H), 5.84 (d, J = 3.9 Hz, 1 H), 6.07-6.19 (m, 2 H).

Conversion of 14 into 15. As analogously described in the preparation of **9**, 15 mg (0.046 mmol) of **14** was converted into 10 mg (60%) of **15** as a colorless oil: TLC, Rf 0.15 (acetone/toluene, 1:1); $[\alpha]^{25}_D$ -18.4° (*c* 0.82, $CHCl_3$); IR (neat) 3450, 1730 cm^{-1}; ^1H NMR δ 1.28, 1.50 (2s, 3 H x 2), 1.22-1.26, 1.31-1.48, 1.70-1.83, 2.01-2.23 (4m, total 10 H), 2.09 (s, 3 H), 2.39-2.61, 3.59-3.71, 3.98-4.01 (3m, total 6 H), 4.49 (t, J = 3.7 Hz, 1 H), 5.03 (dt, J = 12.1, 6.0 Hz, 1 H), 5.83 (d, J = 3.7 Hz, 1 H); ^{13}C NMR δ 17.6, 21.1, 26.0, 26.5, 27.7, 36.5, 40.9, 47.3, 62.9, 73.8, 74.6, 77.2, 79.4, 96.1, 105.9, 111.3, 170.3, 177.8.

Conversion of 14 into Diol 17. As described for the preparation of **11**, compound **14** (62 mg, 0.19 mmol) was hydrolyzed to give crude hemiacetal **16** which was used for next step.

The crude **16** was subjected to glycol cleavage with $NaIO_4$ followed by $NaBH_4$ reduction to give **17** (31.5 mg, 64%) as described in the preparation of **11.** **17** as colorless crystals, mp 96.0-96.5 °C: TLC, Rf 0.31 (acetone/toluene, 1:2); $[\alpha]^{25}_D$ +44.2° (*c* 0.98, $CHCl_3$); IR (neat) 3390, 1730 cm^{-1}; ^1H NMR δ 1.18-1.39 (m, 3 H), 1.50 (tdd, J = 2.0, 3.9, 9.3 Hz, 1 H), 1.56 (tt, J = 2.7, 9.3 Hz, 1 H), 1.80-1.86 (m, 2 H), 1.88 (td, J = 2.9, 10.5 Hz, 1 H), 2.00 (s, 3 H), 2.08 (ddd, J = 1.2, 4.6, 10.5 Hz, 1 H), 2.43-2.48 (m, 1 H), 2.68 (br s, 2 H), 2.86-2.92 (m, 1 H), 3.55-3.71 (m, 3 H), 5.11 (td, J = 1.8, 4.6 Hz, 1 H), 6.11-6.18 (m, 2 H); ^{13}C NMR δ 21.8 23.9, 27.0, 28.4, 30.6, 32.6, 40.1, 43.4, 47.4, 69.0, 70.7, 73.0, 130.8, 134.1, 170.4; HRMS, calcd for $C_{15}H_{22}O_4$ (M^+) *m/z* 266.1516, found 266.1511.

Acetylation of 17. Compound **17** (14 mg, 0.054 mmol) was acetylated with acetic anhydride (1 mL) in pyridine (1 mL) for 4 h, and the reaction mixture was concentrated in vacuo. The residue was purified by column chromatography on silica gel (EtOAc/hexane, 1:4) to give **18** (17 mg, 93%) as colorless crystals, mp 89.5-90.0 °C: TLC, Rf 0.69 (acetone/toluene, 1:3); $[\alpha]^{24}_D$ -3.6 ° (*c* 1.01, $CHCl_3$); IR (neat) 1735 cm^{-1}; ^1H NMR δ 1.15-1.59 (m, 5 H), 1.71 (dt J = 3.4, 15.0 Hz, 1 H), 1.84 (ddd, J = 3.4, 10.2, 15.0 Hz, 1 H), 1.96-2.16 (m, 2 H), 2.01, 2.06, 2.09 (3s, 3 H x 3), 2.42-2.49 (m 2 H), 3.85 (dd, J = 7.3, 10.6 Hz, 1 H), 3.91 (dd, J = 5.1, 10.6 Hz, 1 H), 4.95 (dd, J = 10.1, 10.8 Hz, 1 H), 5.15 (q, J = 3.4 Hz, 1 H), 6.08, 6.15 (2td, each J = 7.3, 1.3 Hz, 1 H x 2); ^{13}C NMR δ 20.9, 21.2, 21.8, 23.8, 27.0, 29.0, 31.3, 32.3, 36.3, 43.8, 44.9, 67.0, 70.3, 71.8, 131.3, 133.5, 170.3, 170.4, 170.9.

Anal. Calcd for $C_{19}H_{26}O_6$: C, 65.13; H, 7.48. Found: C, 64.86, H, 7.74.

Luche Reduction of 1 Followed by Esterification with Sorbic acid: Formation of the Subtrate 20 for the IMDA. To a cold (-15 °C) stirred solution of **1** (1.05 g, 4.99 mmol) in MeOH (20 mL) was added $CeCl_3 \cdot 7H_2O$ (1.86 g, 4.99 mmol). After 15 min stirring at -15 °C, $NaBH_4$ (94 mg, 2.50 mmol) was added to the solution. The solution was stirred at -15 °C for 25 min, and diluted with saturated brine (200 mL). The solution was extracted with EtOAc (100 mL x 3). The combined extracts were dried and concentrated in vacuo to give crude α-allylic alcohol **19** contaminated by the diastereomeric β-allylic alcohol (1.20 g, α:β=ca.10:1 based on the ^1H NMR analysis), which was used for the next step without separation.

To a solution of the mixture (1.20 g) in CH_2Cl_2 (20 mL) were added 4-dimethylaminopyridine (DMAP) (280 mg, 2.5 mmol), 1-ethyl-3-(3-dimethylaminopropyl)carbodiimide hydrochloride (WSCI) (1.05 g, 5.5 mmol), and (2*E*,4*E*)-hexadienoic acid (sorbic acid) (615 mg, 5.5 mmol). After the solution was stirred for 4 h, DMAP (56 mg), WSCI (191 mg) and sorbic acid (112 mg) were added. The solution was stirred for an additional 1 h, and diluted with EtOAc (200 mL). The solution was washed with 0.5 M HCl solution (100 mL), saturated aq $NaHCO_3$ (100 mL), saturated brine (100 mL), successively. The organic layer was dried and concentrated in vacuo. The residue was purified by column chromatography on silica gel (EtOAc/hexane, 1:8 to 1:6) to give **20** (1.34 g, 87%) as a colorless oil, which was unstable on standing at rt and partially decomposed after 1 day, thus used for the intramolecular Diels-Alder cycloaddition immediately after preparation. **20**: TLC, R_f 0.53 (acetone/toluene, 1:8); $[\alpha]^{27}_D$ -123.5 ° (*c* 1.06, $CHCl_3$); IR (neat) 1710, 1640, 1620 cm^{-1}; ^1H NMR δ 1.34, 1.52 (2 s, 3 H x 2), 1.57-1.84 (m, 2 H), 1.86 (d, *J* = 5.5 Hz, 3 H), 2.47-2.54 (m, 1 H), 4.40-4.44 (m, 1 H), 4.61 (t, *J* = 3.3 Hz, 1 H), 5.60-5.66 (m, 2 H), 5.76 (d, *J* = 15.8 Hz, 1 H), 5.88 (d, *J* = 3.3 Hz, 1 H), 6.14-6.27 (m, 3 H), 7.22-7.31 (m, 1 H); ^{13}C NMR δ 18.7, 25.8, 26.1, 27.4, 47.1, 70.7, 75.5, 79.8, 106.1, 111.8, 118.6, 128.3, 129.7, 131.1, 139.8, 145.5, 166.7.

Intramolecular Diels-Alder Cycloaddition of 20: The following reaction was carried out using two sealed tubes. For each compound **20** (176 mg, 0.57 mmol) was dissolved in *o*-xylene (2 mL) and the solution was transferred to a 10 mL Pyrex sealed tube with a screwed stopper. The tube was purged with Ar. The two sealed tubes were heated at 200 °C for 4 h. The combined reaction solutions were concentrated in vacuo. The residue was purified by column chromatography on silica gel (EtOAc/hexane, 1:10 , 1:5 then 1:3) to give an inseparable mixture of **21** and **22** (93 mg, 26%), **23** (21 mg, 6%), and 195 mg (56%) of **20** was recovered. The mixture of **21** and **22** (ca. 7:1 based on the ^1H NMR analysis) was obtained as a colorless oil: TLC, R_f 0.18 (EtOAc/hexane, 1:2); IR (neat) 1770 cm^{-1}; ^1H NMR δ 1.04 (d, *J* = 7.1 Hz, 3 H x 1/8),

1.29 (d, J = 7.1 Hz, 3 H x 7/8), 1.30, 1.44 (2s, 3 H x 2), 1.24-1.39 (m, 2 H), 1.98-2.06, 2.41-2.47, 2.63-2.75, 3.21-3.28 (4m, each 1 H x 1/8), 2.16-2.27 (m, 2 H x 7/8), 2.31-2.38 (m, 1 H x 7/8), 3.04-3.12 (m, 1 H x 7/8), 3.34-3.51 (m, 1 H x 7/8), 3.57 (t, J = 10.1 Hz, 1 H), 4.51 (t, J = 3.8 Hz, 1 H x 7/8), 4.57 (t, J = 3.8 Hz, 1 H x 8), 4.78-4.86 (m, 1 H x 7/8), 4.87-4.97 (m, 1 H x 1/8), 5.81 (d, J = 3.8 Hz, 1 H), 5.83-5.90 (m, 1 H x 7/8), 5.94-5.98 (m, 1 H x 1/8), 6.01 (dt, J = 2.5, 9.2 Hz, 1 H x 7/8), 6.07-6.15 (m, 1 H x 1/8). **23** was obtained as a colorless oil: TLC, R_f 0.25 (EtOAc/hexane, 1:2); $[\alpha]^{25}_D$ +3.9 ° (*c* 1.07, $CHCl_3$); IR (neat) 1780, 1735 cm^{-1}; ^1H NMR δ 1.14 (d, J = 7.7 Hz, 3 H), 1.33, 1.51 (2s, 3 H x 2), 1.37-1.49 (m, 1 H), 1.80 (td, J = 9.9, 13.5 Hz, 1 H), 1.87 (dd, J = 6.5, 10.5 Hz, 1 H), 2.38 (ddd, J = 2.7, 6.5, 13.5 Hz, 1 H), 2.54 (dt, J = 6.5, 14.3 Hz, 1 H), 2.54-2.65 (m, 1 H), 3.04 (dq, J = 14.3, 2.6 Hz, 1 H), 3.83 (t, J = 10.5 Hz, 1 H), 4.58 (t, J = 3.8 Hz, 1 H), 4.70 (dt, J = 9.9, 6.5 Hz, 1 H), 5.66 (dt, J = 9.9, 2.6 Hz, 1 H), 5.89 (d, J = 3.8 Hz, 1 H), 6.09 (dt, J = 9.9, 2.6 Hz, 1 H).

Conversion of the Mixture of 21 and 22 into Dibenzoates 24 and 25. The following reaction was carried out under Ar. To a cold (-78 °C) stirred solution of the inseparable mixture of **21** and **22** (93 mg, 0.30 mmol) in $CHCl_3$ (2 mL) was added Dibal-H (1.0 M solution in toluene, 0.45 mL, 0.45 mmol). The solution was stirred at -78 °C for 20 min and quenched with H_2O (1 mL). The precipitated gels were removed by filtration through a Celite-pad, and washed well with EtOAc. The combined filtrate and washing were washed with saturated brine (10 mL x 3). The organic layer was dried and concentrated in vacuo.

The residual oil (83 mg) was dissolved in EtOH (2 mL) and $NaBH_4$ (11.5 mg, 0.30 mmol) was added. The solution was stirred for 2.5 h and neutralized with Amberlite IR-120 [H^+]. The resin was removed by filtration and washed with EtOH. The combined filtrate and washing were concentrated in vacuo. The residue was purified by column chromatography on silica gel (acetone/toluene. 1:3) to give two diols (73 mg) as an inseparable oily mixture, which was used for benzoylation.

This mixture (73 mg) was dissolved in pyridine (2 mL), and DMAP (58 mg, 0.47 mmol) and benzoyl chloride (0.17 mL, 1.42 mmol) were added. The solution was stirred for 3 h and diluted with EtOAc (20 mL). The solution was washed with saturated aq $NaHCO_3$ (10 mL x 3). The organic layer was dried and concentrated in vacuo. The residue was purified by column chromatography on silica gel (EtOAc/hexane, 1:6) to give **24** (105 mg, 67%) and **25** (16 mg, 10%), both as colorless oils.

24: TLC, R_f 0.60 (EtOAc/hexane, 1:2); $[\alpha]^{26}_D$ -22.9° (*c* 1.15, $CHCl_3$); IR (neat) 1720, 1605 cm^{-1}; ^1H NMR δ 1.25 (d, J = 7.6 Hz, 3 H), 1.32, 1.55 (2s, 3 H x 2), 1.54-1.66 (m, 1 H), 2.02 (q, J = 12.4 Hz, 1 H), 2.05-2.13 (m, 1 H), 2.25-2.34 (m, 1 H), 2.48-2.56 (m, 1 H), 2.84-2.98 (m, 2 H), 3.90 (t, J = 10.8 Hz, 1 H), 4.29 (t, J = 9.8 Hz,

1H), 4.53 (t, J = 3.8 Hz, 1 H), 5.20 (dd, J = 4.1, 9.8 Hz, 1H), 5.42 (dt, J = 12.4, 6.1 Hz, 1 H), 5.61 (d, J = 10.4 Hz, 1 H), 5.85 (d, J = 3.8 Hz, 1 H), 5.90 (dt, J = 10.4, 2.8 Hz, 1 H), 7.44-7.59, 8.05-8.13 (2m, 6 H, 4 H); ^{13}C NMR δ 19.7, 26.1, 26.3, 27.5, 34.1, 34.6, 39.4, 42.3, 49.1, 67.6, 74.8, 75.1, 77.2, 78.8, 105.9, 111.4, 124.7, 127.9, 128.4, 128.5, 129.6, 129.9, 130.3, 132.3, 132.9, 133.1, 165.9, 166.0.

Anal. Calcd for $C_{31}H_{34}O_7$: C, 71.80; H, 6.61. Found: C, 71.55, H, 6.75.

25: TLC, R_f 0.53 (EtOAc/hexane, 1:2); $[\alpha]^{26}_D$ -70.5 ° (c 0.40, $CHCl_3$); IR (neat) 1720, 1600 cm^{-1}; ^{1}H NMR δ 1.08 (d, J = 7.3 Hz, 3 H), 1.33, 1.52 (2s, 3 H x 2), 1.57-1.62 (m, 1 H), 1.83 (dd, J = 3.5, 11.0 Hz, 1 H), 2.02 (q, J = 13.3 Hz, 1 H), 2.32 (dt, J = 13.3, 4.8 Hz, 1 H), 2.61-2.69 (m, 1 H), 2.82-2.97 (m, 2 H), 3.78 (t, J = 11.0 Hz, 1 H), 4.29 (t, J = 10.0 Hz, 1 H), 4.61 (t, J = 3.7 Hz, 1 H), 5.11-5.19 (m, 1 H), 5.38-5.46 (m, 1 H), 5.74 (dd, J = 4.8, 10.3 Hz, 1 H), 5.87 (d, J = 3.7 Hz, 1 H), 5.85-5.92 (m, 1 H), 7.40-7.61, 8.05-8.14 (2m, 6 H, 4 H); ^{13}C NMR δ 22.1, 26.1, 26.3, 27.8, 29.2, 33.9, 34.2, 43.9, 48.0, 67.9, 75.2, 77.2, 80.0, 105.9, 111.8, 124.2, 128.1, 128.4, 128.5, 129.5, 129.6, 129.7, 129.9, 130.2, 131.8, 132.9, 133.1, 165.9, 166.1.

Anal. Calcd for $C_{31}H_{34}O_7$: C, 71.80; H, 6.61. Found: C, 71.97, H, 6.91.

Conversion of 23 into 26. The following reaction was carried out under Ar. To a cold (-78 °C) stirred solution of **23** (20 mg, 0.066 mmol) in $CHCl_3$ (1 mL) was added Dibal-H (1.0 M solution in toluene, 0.10 mL, 0.1 mmol). The solution was stirred at -78 °C for 20 min and quenched with H_2O (1 mL). The precipitated gels were removed by filtration through a Celite-pad and washed with EtOAc. The combined filtrate and washing were washed with saturated brine (10 mL x 3). The organic layer was dried and concentrated in vacuo.

The residue was dissolved in EtOH (1 mL) and $NaBH_4$ (2.5 mg, 0.06 mmol) was added. The solution was stirred for 1 h and neutralized with Amberlite IR-120 [H$^+$]. The resin was removed by filtration, and washed with MeOH. The filtrate and washing were concentrated in vacuo. The residue was purified by column chromatography on silica gel (acetone/toluene, 1:5) to give **26** (13 mg, 65%) as colorless crystals, mp 152.0-153.0 °C; TLC, R_f 0.36 (acetone/toluene, 1:2); $[\alpha]^{25}_D$ -1.4 ° (c 0.72, $CHCl_3$); IR (neat) 3300 cm^{-1}; ^{1}H NMR δ 1.02 (d, J = 7.0 Hz, 3 H), 1.31, 1.46 (2s, 3 H x 2), 1.38-1.49 (m, 1 H), 1.66 (dd, J = 4.0, 11.0 Hz, 1 H), 1.81 (q, J = 12.0 Hz, 1 H), 1.78-1.84 (br, 1 H), 1.95 (dt, J = 12.0, 4.0 Hz, 1 H), 2.28 (dt, J = 8.9, 4.0 Hz, 1 H), 2.37-2.46 (m, 1 H), 2.48-2.58 (m, 1 H), 3.40 (dd, J = 7.7, 10.6 Hz, 1 H), 3.66 (t, J = 11.1 Hz, 1 H), 3.78 (dd, J = 2.6, 10.6 Hz, 1 H), 3.92 (dt, J = 12.0, 4.0 Hz, 1 H), 4.40-4.50 (br, 1 H), 4.56 (t, J = 3.8 Hz, 1 H), 5.41 (dd, J = 2.2, 10.3 Hz, 1 H), 5.76-5.82 (m, 1 H), 5.80 (d, J = 3.8 Hz, 1 H); ^{13}C NMR δ 20.7, 26.2, 26.3, 28.6, 29.5, 37.1, 39.6, 44.2, 47.8, 68.9, 74.2, 76.2, 80.2, 105.9, 111.8, 125.2, 132.7.

Anal. Calcd for $C_{17}H_{26}O_5$: C, 65.78; H, 8.44. Found: C, 65.52, H, 8.65.

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8. $AlCl_3$ (1.2 eq., CH_2Cl_2, 0 °C 1.5 h) also gave **3** (20%) and **4** (44%), $EtAlCl_2$ or Et_2AlCl did not give any products.
9. The following Lewis acids were examined: $AlCl_3$ (toluene, 40 °C, 5 days); Et_2AlCl (CH_2Cl_2, -78 °C to rt, 1 day); $ZnCl_2$ (CH_2Cl_2, -15 °C to rt, 1 day); $BF_3{\bullet}OEt_2$ (CH_2Cl_2, -15°C to rt, 4 h); TMSOTf (CH_2Cl_2, -15°C to rt, 3 h).
10. When each **5** or **6** was independently subjected to the thermal conditions (200 °C, 1 day), no interconversion was observed. These results indicated that thermal retro-Diels-Alder process did not occur under the conditions used.
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12. Although a trace amount of the diastereomeric β-allylic alcohol could not separated at this stage, this minor component was cleanly removed after the mixture was converted into their *tert*-butyldimethylsilyl ethers. The major α-silylated product was obtained in 87% yield from **1**. The minor β-silyl ether was obtained in 1% yield, and a mixture of them (10%) was also obtained. From these results, we estimated that the diastereoselectivity of the Luche reduction of **1** is more than 8 to 1. Desilylation of the α-silyl ether provided the diastereomerically homogeneous allylic alcohol **19**, which was identical with our previously reported sample,[4] in all respects.
13. Prolonging the reaction time for completion of the Diels-Alder cycloaddition of the subtrate **20** caused partial decomposition of **20**, and the combined yield of **21-23** reduced significantly.
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