~23 kcal/mol and thus configuration stability at 22 °C.[25] These authors claim a lower limit of ~7.1 for the sum of the electronegativities of CH_3O and X in $MeCO_2CH_2$-$(CH_3)_2CN(X)OMe$. The related series, $CF_3N(F)CF_2CF_3$,[22] $ClCF_2CF_2N(Cl)CF_3$,[26] CF_3CF_2NFCl,[23] CF_3CF_2NFBr,[7] and $FSO_2OCF_2N(F)OSO_2F$,[7] provides an interesting comparison in this regard. If the contribution of the alkyl groups C_2F_5, $ClCF_2CF_2$, and FSO_2OCF_2 are all similar, the sum of the electronegativities of the other two substituents on nitrogen can be compared. Since the electronegativity of the CF_3 group is near 3.3 on the Pauling scale,[27] and that of FSO_2O is close to 3.8,[16c] the sums for the aforementioned five compounds are 7.3, 6.5, 7.2, 7.0, and 7.8, respectively, but only the last three compounds exhibit configuration stability at 22 °C. Clearly, the prediction of inversion barriers on the basis of the electronegativities of the substituents on nitrogen is only a very approximate guide.

In the near future, we hope to prepare $ClCF_2CF_2N(X)OCF_3$ (X = F, Cl). These two compounds would provide interesting insight into the effect of electronegativities on inversion barriers in acyclic nitrogen compounds. The CF_3O group has a value of at least 3.8.[28]

Acknowledgment. The financial support of this research by the U.S. Army Research Office (Contract No. DAAG29-82-K-0188 and DAAG29-83-K6173) and the National Science Foundation (CHE-8217217) is gratefully acknowledged.

Registry No. CF_2=NCl, 28245-33-2; CF_3NCl_2, 13880-73-4; CF_3NClBr, 88453-17-2; $C_2F_5NCl_2$, 677-66-7; $C_3F_7NCl_2$, 662-54-4; FSO_2OCl, 13997-90-5; FSO_2OBr, 13997-93-8; Cl_2, 7782-50-5; Br_2, 7726-95-6; BrCl, 13863-41-7; CF_2=NF, 338-66-9; CsF, 13400-13-0; KF, 7789-23-3; NaF, 7681-49-4; LiF, 7789-24-4; C_3F_7NBrCl, 91523-61-4; $C_2F_5NBr_2$, 83696-32-6; C_2F_5NClBr, 91523-62-5; CF_3NBr_2, 88453-18-3; $CF_3\overline{NCF_2NCl}$, 91523-63-6; $CF_3\overline{NCF_2NH}$, 91523-64-7.

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Synthesis and Highly Regioselective Diels–Alder Reaction of Functionalized Isoprenes Involving a Terminal Alkoxy Group and Chemical Modification of the Resulting Adducts

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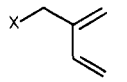
A variety of functionalized isoprenes involving a terminal alkoxy group (**2** and **3**) were newly synthesized according to eq 1, 2, and 3. These compounds proved to undergo a cycloaddition with various unsymmetric dienophiles highly regioselectively without a Lewis acid catalyst. Moreover, the resulting adducts **11** were transformed to cyclohexadienes **12** through elimination of an alcohol.

The Diels–Alder reaction provides powerful synthetic tools for constructing six-membered rings. It should be noticed, however, that the reaction must proceed regioselectively when unsymmetric dienes and dienophiles are employed. As for butadiene derivatives, this restriction seems to be almost removed through the extensive studies by both Danishefsky[1] and Overman.[2] On the other hand, there still remains the problem of regioselectivity unresolved in the case of isoprene derivatives, whose Diels–Alder reaction with various dienophiles should afford the most promising synthetic method for cyclic terpenoids.[3] For the synthetic purpose, appropriate functionalization of the isoprene unit is also desirable. Accordingly, it seems of great interest to develop a new method for functionalized isoprenes suitable for the regioselective Diels–Alder reaction.

So far, only a few studies have been made on the preparation of functionalized isoprenes. For example, 2-(halomethyl)-1,3-butadienes, **1a** and **1b**, have been obtained in ca. 10% yield by thermolysis of halides of the isoprene/SO_2 adduct[4,5] and the bromomethyl compound has been converted into the hydroxymethyl derivative **1c**.[6] We have developed a new method for compounds **1a** and **1c** employing 2-(hydroxymethyl)-4-(phenythio)-1-butene.[7] More recently, the trimethylsilyl and trimethylstannyl derivatives **1d** and **1e** have been reported.[8] However, the Diels–Alder reaction of these dienes with unsymmetric dienophiles, in general, resulted in unsatisfactory regioselectivity, though **1d** and **1e** gave rise to improvement of



1a, X = Cl
b, X = Br
c, X = OH
d, X = Me_3Si
e, X = Me_3Sn

(1) (a) Danishefsky, S.; Kitahara, T.; Yan, C. F.; Morris, J. *J. Am. Chem. Soc.* **1979**, *101*, 6996. (b) Danishefsky, S.; Yan, C. F.; Singh, R. K.; Gammill, R. B.; McCurry, P. M., Jr.; Fritsch, N.; Clardy, J. *Ibid.* **1979**, *101*, 7001.
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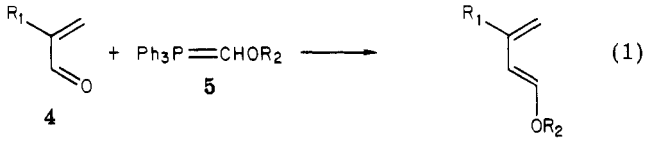
0022-3263/84/1949-3595$01.50/0

the regioselectivity by use of an aluminum chloride catalyst.[8] Since introduction of an electron-donating group at the terminal position of the diene unit would increase the polarization of this moiety which is expected to improve the regioselectivity, we have turned our attention to synthesize functionalized isoprenes involving a terminal alkoxy group (**2** and **3**). It is further expected that introduction of an alkoxy group into the Diels–Alder adducts should expand the scope of synthetic utility. In this paper, we describe various synthetic methods for **2** and **3** and show that these compounds indeed undergo almost complete regioselective Diels–Alder reaction with unsymmetric dienophiles even without a Lewis acid catalyst. Moreover, chemical modification of an alkoxy group of the resultant Diels–Alder adducts giving rise to cyclohexadienes also will be reported.[9]

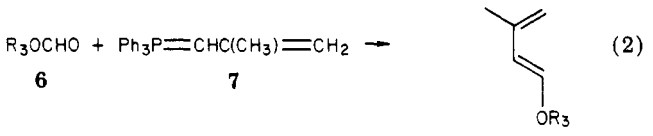
Results and Discussion

Synthesis of Dienes. Two types of dienes, mono- and difunctionally substituted isoprene derivatives, **2** and **3**, were synthesized. The former compounds **2** were obtained by the following procedures (eq 1 and 2). The Wittig



(1)

2a, $R_1 = C_5H_{11}$; R_2 = Me
b, R_1 = Me; R_2 = ME



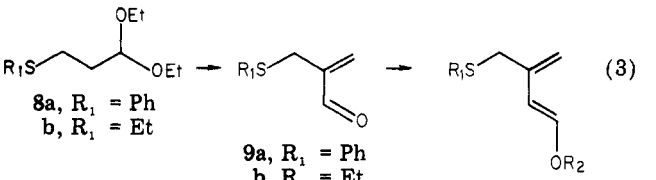
(2)

2b, R_3 = ME
c, R_3 = $PhSCH_2CH_2$
d, R_3 = $PhSeCH_2CH_2$

condensation of aldehydes **4** with the ylide **5** at −30 to 0 °C afforded methoxy and β-methoxyethoxy (ME) derivatives, **2a** and **2b**, in 37% and 43% yields, respectively. The dienes thus obtained were contaminated with a small amount of isopropylcyclohexylamine (ICA), which were derived from lithium isopropylcyclohexylamide(LICA) employed for generation of **5**. ICA serves to stabilize dienes, although these compounds could not be stored only for a day in the refrigerator even in the presence of ICA. Diene **2b** could be distilled and purified by column chromatography, and thus it was subjected to the Diels–Alder reaction immediately after purification, while **2a** was used without purification on account of its high instability. NMR spectra showed that the *E*/*Z* ratio of these dienes are 70:30, respectively.

Next, we have attempted to synthesize dienes which involve a β-(phenylthio)ethoxy or β-(phenylseleno)ethoxy group. For this purpose, the Wittig condensation depicted as eq 2 was developed.[10] The method was first applied to prepare **2b** by treating β-methoxyethyl formate with the ylide **7** at 0 °C followed by warming to room temperature. Actually a 35% yield of **2b** was realized after Kugelrohr distillation. Then, corresponding β-(phenylthio)ethoxy and β-(phenylseleno)ethoxy derivatives were obtained by the analogous method in 40% and 50% yields, respectively. The former compound **2c** was distillable while the latter **2d** could not be distilled without decomposition. The dienes are quite unstable and, therefore, they should be used immediately after isolation. It is noteworthy that dienes obtained according to this method involve *E* isomers only.

The procedure for difunctional dienes **3a–c** is shown below (eq 3). β-Alkythio acetals **8** were converted into



8a, R_1 = Ph
b, R_1 = Et

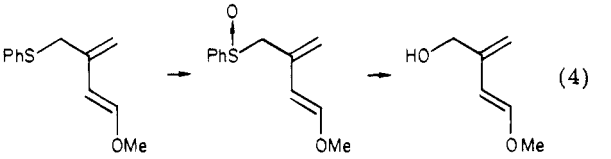
9a, R_1 = Ph
b, R_1 = Et

(3)

3a, R_1 = Ph; R_2 = Me
b, R_1 = Et; R_2 = Me
c, R_1 = Ph; R_2 = ME

enals **9** in 50–65% yields by treatment with formalin and $Me_2NH{\cdot}HCl$.[11] Then, **9** was allowed to react with **5** affording **3a–c** in 35–37% yields after distillation and column chromatography. These dienes are relatively stable as compared with others described above, and accordingly can be stored for a day in a refrigerator without any appreciable decomposition.

Finally, the Evans rearrangement of the sulfoxide derived from **3a** afforded hydroxymethyl derivative **3d** (eq 4). All of these difunctional dienes involve *E*/*Z* isomers

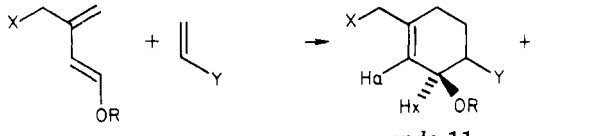


3a **3d**

(4)

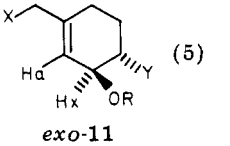
in a 70:30 ratio. The dienes obtained in this study are, in general, too unstable to permit successful elemental analyses. The formation of these compounds, however, was apparent from the fact that their Diels–Alder adducts gave correct analytical data.

Diels–Alder Reaction. The dienes thus obtained proved to undergo a cycloaddition with various unsymmetric dienophiles without a Lewis acid catalyst. The results are summarized in Table I. GLC of the adducts gave rise to two peaks and ^{13}C NMR spectra exhibited a pair of signals for each olefinic carbon. That these mixtures are stereoisomers was confirmed by ^1H NMR spectra which gave rise to olefinic proton signals diagnostic of an endo/exo mixture of the para regioisomer.[1a] Namely, Ha



10a, Y = SO_2Ph
b, Y = COMe
c, Y = CO_2Me
d, Y = $CO(CH_2)_2CH{=}C(CH_3)_2$

endo-**11**



(5)

exo-**11**

of the endo adducts appears at lower fields with larger *J*ax

(9) A part of this study has been published in a preliminary form: Mandai, T.; Osaka, K.; Wada, T.; Kawada, M.; Otera, J. *Tetrahedron Lett.* **1983**, *24*, 1171. Mandai, T.; Osaka, K.; Kawagishi, M.; Kawada, M.; Otera, J. *Synth. Commun.*, in press.
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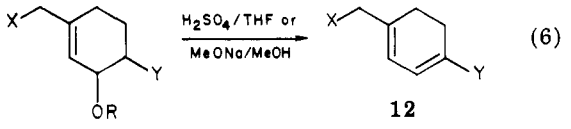
constants (5–6 Hz) as compared with those of their exo counterparts ($J < 2$ Hz). This is completely consistent with the result of a fully characterized cycloadduct between 1-methoxy-3-(trimethylsiloxy)-1,3-butadiene and *trans*-methyl crotonate.[1a] As a result, it is seen that the cycloaddition proceeds highly regioselectively to afford the para isomer.

Conversion of Adducts into Cyclohexadienes. It was found that the alkoxy group of adducts **11** could be eliminated to give cyclohexadienes derivatives **12** under either acidic or basic conditions (eq 6). As summarized in Table



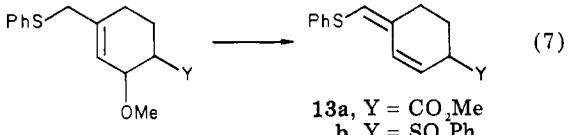
(6)

11 **12**

II, the adducts derived from α,β-enones are smoothly converted into cyclohexadienes by 20% H_2SO_4/THF (entries 1–4, and 6). By contrast, basic condition, in general, failed to transform these adducts to cyclohexadienes except for two cases. As indicated in entry 5, **11b** affords an elimination product only in 27% yield on treatment with a stoichiometric amount of MeONa in MeOH for 1 h. Prolonged reaction gives rise to decomposition of the products. Adduct **11c** is the only compound that undergoes a successful elimination under basic conditions (entry 7). Interestingly, only an endo isomer is consumed completely and an exo counterpart (30%) is recovered unchanged after 1 h. It should be noted that acidic elimination of other adducts also proceeds much faster for endo isomers. It may be said therefore that the trans elimination is facilitated under both conditions.

Unsatisfactory basic elimination of methyl vinyl ketone adducts in contrast with **11c** may be attributable to the presence of a base-sensitive acetylmethyl group. The adducts derived from methyl acrylate **11n** and phenyl vinyl sulfone **11o** proved to resist acidic elimination of methanol (entries 8 and 10). This may be rationalized in terms of the reduced acidity of the hydrogen α to a methoxycarbonyl or phenylsulfonyl group as compared with that of a proton α to a carbonyl group. Elimination of methanol from these compounds, however, was achieved under basic conditions (entries 9 and 11).

To our regret, no successful results were obtained for **11g** and **11h** which involve a phenylthio group in an allylic position. Sole products identified after various reactions



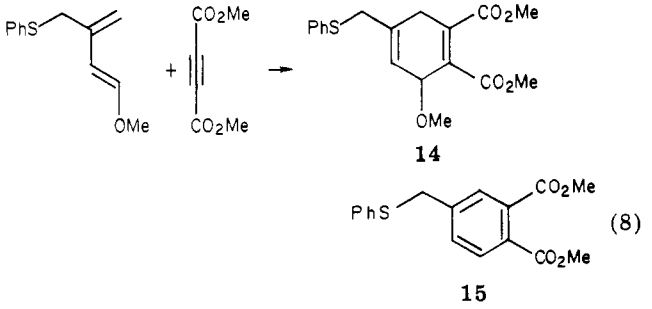
(7)

11g, Y = CO_2Me
h, Y = SO_2Ph

13a, Y = CO_2Me
b, Y = SO_2Ph

were **13a** (4.5%, *t*-BuOK/*t*-BuOH, room temperature, 12 h) and **13b** (10.5%, MeONa/MeOH, room temperature, 12 h) from **11g** and **11h**, respectively (eq 7).

As shown in eq 8, the reaction of methoxydienes with dimethyl acetylenedicarboxylate yielded the mixture of the adduct **14** and the aromatic compound **15**, which is derived from **14** by elimination of methanol.[12] This mixture can be totally transformed to **15** in 40% yield by passing through a silica gel column.



14

15

(8)

In conclusion, functionalized isoprenes obtained in this study seem to be useful building blocks for cyclic terpenoids due to high regioselectivity of the Diels–Alder reaction with a variety of unsymmetric dienophiles and facile conversion into cyclohexadienes. Synthetic application of these compounds is now in progress in our laboratory.

Experimental Section

^1H and ^{13}C NMR spectra were recorded on a Hitachi R-24B (60 MHz) and a JEOL FX-100 (100 MHz) spectrometers, respectively, with Me_4Si as an internal standard. IR spectra were obtained as neat films on a JASCO IRA-I spectrometer. GLC analyses were carried out on a Hitachi 163 gas chromatography using a 3 mm × 3 m column packed with SE-30.

Commercially available reagents were distilled before use and solvents were purified by standard methods. All reactions were conducted under a nitrogen atmosphere. The phosphonium salts **5** and **7** were prepared from triphenylphosphine and corresponding chlorides.[13,14] The formates **6** were obtained by heating formic acid and corresponding alcohols at 60 °C.

1-Methoxy-3-*n*-pentyl-1,3-butadiene (2a). To a THF solution (15 mL) of ICA (7.13 g, 48 mmol) was added dropwise *n*-BuLi (32 mL of 1.5 N *n*-hexane solution, 48 mmol) at 0 °C. After being stirred for 20 min, the resulting LICA solution was added dropwise to a THF solution (30 mL) of triphenyl(methoxymethyl)-phosphonium chloride (TMPC) (19.3 g, 50 mmol) at −78 °C. The reaction mixture was warmed up to −30 °C and 2-methylene-1-heptanal[15] (3.0 g, 20 mmol) in 5 mL of THF was added to this mixture over a period of 15 min, during which time the temperature of the mixture rose to 0 °C. After being stirred for 1 h at room temperature, the reaction mixture was poured into 300 mL of hexane and the organic layer was washed with water. Drying ($MgSO_4$) and evaporation yielded **2a** as an oil that was used for the next step without further purification (1.14 g, 37%): ^1H NMR (CCl_4) δ 0.89 (t, 3 H, CH_3, J = 6 Hz), 1.08–1.80 (m, 6 H, CCH_2O), 1.80–2.32 (m, 2 H, CH_2C=), 3.49 (s, 2.1 H, OCH_3, *trans*), 3.58 (s, 0.9 H, OCH_3, cis), 4.51–4.73 (m, 2.3 H, CH_2=C, CH=CO, cis), 5.33 (d, 0.7 H, CH=CO, trans, J = 13 Hz), 5.69 (d, 0.3 H, C=CHO, cis, J = 7 Hz), 6.48 (d, 0.7 H, C=CHO, trans, J = 13 Hz).

1-(β-Methoxyethoxy)-3-methyl-1,3-butadiene (2b). This compound was prepared employing methacrolein and triphenyl [(β-methoxyethoxy)methyl]phosphonium chloride (TMEPC) as described for **2a**. Purification was performed by distillation followed by column chromatography (silica gel, 80:1 hexane–ether): yield 43%; ^1H NMR (CCl_4) δ 1.75 (s, 0.9 H, CH_3), 1.90 (s, 2.1 H, CH_3), 3.31 (s, 3 H, OCH_3), 3.37–3.94 (m, 4 H, OCH_2CH_2O), 4.02–4.87 (m, 2.3 H, =CH_2, CH=CO, cis), 5.50 (d, 0.7 H, CH=CO, trans, J = 13 Hz), 5.79 (d, 0.3 H, =CHO, cis, J = 7 Hz), 6.38 (d, 0.7 H, =CHO, trans, J = 13 Hz).

1-[β-(Phenylthio)ethoxy]-3-methyl-1,3-butadiene (2c). To a THF solution (50 mL) of triphenylmethallylphosphonium chloride (13.2 g, 37.2 mmol) was added *n*-BuLi (23 mL, 35.4 mmol) at 0 °C. The mixture was stirred for 1 h at room temperature and then β-(phenylthio)ethyl formate (3.39 g, 18.6 mmol) in THF (5 mL) was added. After being stirred for 1 h at room temperature, the reaction mixture was poured into ice water followed by extraction with hexane. Drying ($MgSO_4$) and evaporation of the

(12) This type of elimination is very common for methoxybutadienes: ref 1b. Dowd, P.; Weber, W. *J. Org. Chem.* **1982**, *47*, 4774. Hiranuma, H.; Miller, S. I. *Ibid.* **1982**, *47*, 5083.

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(14) Corey, E. J.; Gras, J. L.; Ulrich, P. *Tetrahedron Lett.* **1976**, 809.
(15) This aldehyde was prepared by the analogous method for **9**.

Table I. Diels–Alder Reaction of 2 and 3 with Various Unsymmetric Dienophiles

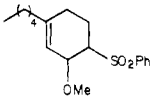
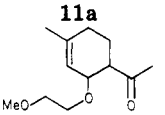
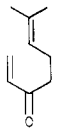
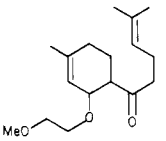
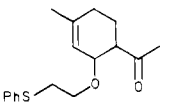
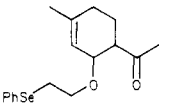
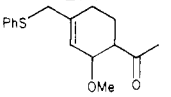
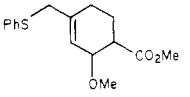
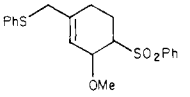
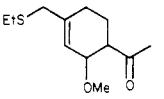
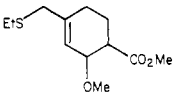
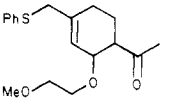
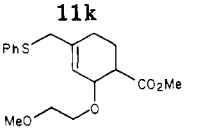
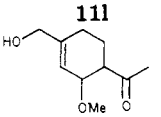
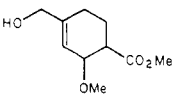
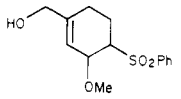
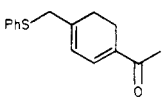
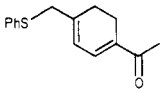
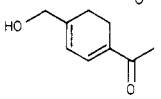
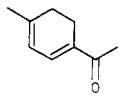
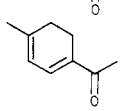
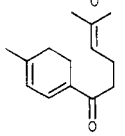
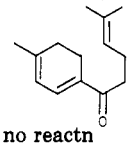
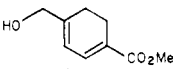
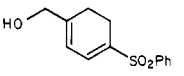
			reaction conditions					
entry	diene	dienophile	solvent[a]	temp, °C	time, h	product	yield,[b] %	endo/exo[c]
1	**2a**		T	110	60	 **11a**	53	38:62
2	**2b**		B	rt[d]	24	 **11b**	76	74:26
3	**2b**		B	60	6	 **11c**	70	72:28
4	**2c**		B	80	10	 **11d**	80	71:29
5	**2d**		B	80	10	 **11e**	80	71:29
6	**3a**		B	rt[d]	24	 **11f**	73	81:19
7	**3a**		B	80	11	 **11g**	71	68:32
8	**3a**		T	110	48	 **11h**	99	23:77
9	**3b**		B	rt[d]	70	 **11i**	70	81:19
10	**3b**		B	80	11	 **11j**	78	75:25
11	**3c**		B	rt[d]	24	 **11k**	57	81:19
12	**3c**		B	80	24	 **11l**	54	63:37
13	**4**		B	rt[d]	24	 **11m**	63	71:29
14	**4**		B	80	10	 **11n**	88	82:18

Table I (Continued)

entry	diene	dienophile	reaction conditions: solvent[a]	temp, °C	time, h	product	yield,[b] %	endo/exo[c]
15	4		T	110	40	 **11o**	65	37:63

[a] T = toluene, B = benzene. [b] Isolated yields based on a *Z* isomer of dienes except when phenyl vinyl sulfone was employed as a dienophile. For this case, yields are based on a dienophile. [c] Based on GLC and ^{1}NMR spectra. [d] rt = room temperature.

Table II. Oxidative Dealkoxylation of Adducts 11.

entry	adduct	reactn conditn[a]	product	yield, %
1	**11f**	A, 24 h		85
2	**11k**	A, 24 h		75
3	**11m**	A, 24 h		95
4	**11b**	A, 24 h		65
5	**11b**	B, 1 h		27
6	**11c**	A, 24 h		43
7	**11c**	B, 1 h		67
8	**11n**	A, 39 h	no reactn	
9	**11n**	B, 12 h		48
10	**11o**	A, 40 h	no reactn	
11	**11o**	B, 12 h		50

[a] A, 20% H_2SO_4/THF, room temperature; B, MeONa/MeOH, room temperature.

organic layer yielded an oil that was distilled to give **2c** (1.62 g, 40%): bp 130 °C (0.01 mm, Kugelrohr bath temperature); ^{1}H NMR (CCl_4) δ 1.70 (s, 3 H, CH_3), 3.02 (t, 2 H, CH_2S, *J* = 7 Hz), 3.82 (t, 2 H, OCH_2, *J* = 7 Hz), 4.64 (m, 2 H, $=CH_2$), 5.47 (d, 1 H, CH=CO, *J* = 13 Hz), 6.34 (d, H, C=CHO, *J* = 13 Hz), 6.94–7.46 (m, 5 H, Ph).

1-[β-(Phenylseleno)ethoxy]-3-methyl-1,3-butadiene (2d). This compound was prepared by the same method for **2c** except employing β-(phenylseleno)ethyl formate in place of the β-phenylthio analogue in 50% yield. This compound was used for the next reaction without further purifiction on account of its high instability: ^{1}H NMR (CCl_4) δ 1.71 (s, 3 H, CH_3), 2.98 (t, 2 H, CH_2Se, *J* = 7 Hz), 3.85 (t, 2 H, OCH_2, *J* = 7 Hz), 4.58 (m, 2 H, $=CH_2$), 5.43 (d, 1 H, CH=CO, *J* = 13 Hz), 6.33 (d, 1 H, =CHO, *J* = 13 Hz), 6.90–7.51 (m, 5H, Ph).

3-(Phenylthio)-2-methylenepropanal (9a). The mixture of acetal **8a** (24 g, 100 mmol), 37% formalin (16.2 g, 200 mmol), Me_2NH·HCl (16.5 g, 200 mmol), and hydroquinone (11 mg, 0.1 mmol) was stirred at 100 °C for 2 h. The reaction mixture was poured into ice water followed by extraction with ether. The organic layer was washed with sodium bicarbonate solution and dried ($MgSO_4$). Evaporation of ether yielded an oil that was distilled to give **9a** (8.9 g, 50%): bp 95 °C (0.1 mm); ^{1}H NMR (CCl_4) δ 3.64 (s, 2 H, CH_2S), 5.96 (s, 1 H, =CH), 6.23 (s, 1 H, =CH), 7.20 (br s, 5 H, Ph), 9.48 (s, 1 H, CHO). This compound cannot be stored more than 1 h after isolation on account of its high susceptibility to polymerization.

3-(Ethylthio)-2-methylenepropanal (9b). This compound was prepared as described for **9a**: yield 53%; bp 90 °C (20 mm); ^{1}H NMR (CCl_4) δ 1.25 (t, 3 H, CH_3, *J* = 7 Hz), 2.45 (q, 2 H, CH_2, *J* = 7 Hz), 3.27 (s, 2 H, SCH_2C=), 6.00 (s, 1 H, =CH), 6.31 (s, 1 H, =CH) 9.50 (s, 1 H, CHO). This compound also cannot be stored more than 1 h after isolation.

1-Methoxy-3-[(phenylthio)methyl]-1,3-butadiene. (3a). To a THF solution (40 mL) of TMPC (25.7 g, 75 mmol) was added LICA (70 mmol) in THF (20 mL) at −78 °C. The mixture was warmed to −30 °C and then **9a** (8.9 g, 50 mmol) in THF (10 mL) was added, during which time the temperature of the reaction mixture rose to 0 °C. After being stirred for 1 h at room temperature, the reaction mixture was poured into hexane (400 mL). The organic layer was washed with water, dried ($MgSO_4$), and evaporated to leave an oil that was distilled and further chromatographed on silica gel (100:1 hexmane–ether) (3.6 g, 35%): bp 130 °C (0.1 mm, Kugelrohr bath temperature); ^{1}H NMR (CCl_4) δ 3.57 (s, 3 H, OCH_3), 3.64 (s, 2 H, SCH_2), 4.70–5.10 (m, 2.3 H, $C=CH_2$, CH=CO, cis), 5.38 (d, 0.7 H, CH=CO, trans, *J* = 13 Hz), 5.85 (d, 0.3 H =CHO, cis, *J* = 7 Hz), 6.65 (d, 0.7 H, =CHO, trans, *J* = 13 Hz), 6.95–7.40 (m, 5 H, Ph).

1-Methoxy-3-[(ethylthio)methyl]-1,3-butadiene (3b). This compound was prepared as described for **3a**: yield 37%; bp 150 °C (25 mm, Kugelrohr bath temperature); ^{1}H NMR (CCl_4) δ 1.18 (t, 3 H, CH_3, *J* = 7 Hz), 2.41 (q, 2 H, CH_2S, *J* = 7 Hz), 3.17 (s, 2 H, SCH_2C=), 3.55 (s, 2.1 H, CH_3O, trans), 3.65 (s, 0.9 H, CH_3O, cis), 4.60–5.21 (m, 2.3 H, $=CH_2$, CH=CO, cis), 5.35 (d, 0.7 H, CH=CO, trans, *J* = 13 Hz), 5.86 (d, 0.3 H, C=CHO, cis, *J* = 7 Hz), 6.70 (d, 0.7 H, C=CHO, trans, *J* = 13 Hz).

1-(β-Methoxyethoxy)-3-[(phenylthio)methyl]-1,3-butadiene (3c). This compound was prepared as described for **3a**: yield 36%, bp 150 °C (0.1 mm, Kugelrohr bath temperature); ^{1}H NMR (CCl_4) δ 3.29 (s, 3 H, OCH_3), 3.35–4.04 (m, 4 H, OCH_2CH_2O), 3.55 (s, 2 H, SCH_2), 4.65–5.10 (m, 2.3 H, $=CH_2$, CH=CO, cis), 5.43 (d, 0.7 H, CH=CO, trans *J* = 13 Hz), 5.94 (d, 0.3 H, =CHO, cis, *J* = 7 Hz), 6.64 (d, 0.7 H, =CHO, trans, *J* = 13 Hz), 6.95–7.40 (m, 5 H, Ph).

1-Methoxy-3-(hydroxymethyl)-1,3-butadiene (3d). To a methanol solution (12 mL) of **3a** (1.03 g, 5 mmol) was added 30% H_2O_2 solution (2 mL) at 0 °C. After being stirred for overnight, the reaction mixture was gradually poured into an ice-cooled Na_2SO_3 solution and extracted with dichloromethane. The organic layer was washed with sodium bicarbonate solution, dried ($MgSO_4$), and evaporated. The sulfoxide (1.05 g, 4.7 mmol) thus obtained was heated with diethylamine in dry methanol under reflux for 12 h. Then, the reaction mixture was evaporated and the resulting oil was chromatographed on silica gel (6:1 hexane–ethyl acetate) (0.17 g, 30%): ^{1}H NMR (CCl_4) δ 3.54 (s, 2.1 H, OCH_3, trans), 3.68 (s, 0.9 H, OCH_3, cis), 4.08 (s, 2 H, OCH_2C=), 4.70–5.00 (m, 2.3 H, $=CH_2$, CH=CO, cis), 5.35 (d, 0.7 H, CH=CO, trans, *J* = 13 Hz), 5.79 (d, 0.3 H, =CHO, cis, *J* = 7 Hz), 6.64 (d, 0.7 H, =CHO, trans, *J* = 13 Hz).

Diels–Alder Reaction. Benzene solution (10 mL) containing diene (1 mmol), dienophile (10–15 mmol) except for phenyl vinyl sulfone, and hydroquinone (0.1 mmol) was stirred under the conditions shown in Table I. The reaction mixture was evaporated and the residue was chromatographed to give an adduct and an

unreacted *Z* diene. For the reaction with phenyl vinyl sulfone, excess diene (diene/dienophile molar ratio 2:1) was employed. The adducts thus obtained gave correct analytical and NMR spectral data.

When **3a** (206 mg, 1 mmol) was allowed to react with dimethyl acetylenedicarboxylate (1 mL, 12 mmol) in benzene under reflux for 24 h, a crude mixture of **14** and **15** (1:1) resulted. Column chromatography of this mixture on silica gel (15:1 hexane–ethyl acetate) yielded pure **15** (126 mg, 40%).

Preparation of Cyclohexadienes 12 (Typical Example). Method A. To a THF solution (15 mL) of **11f** (276 mg, 1 mmol) was added 2 mL of 20% H_2SO_4 at 0 °C and the resulting solution was stirred at this temperature for 24 h. The reaction mixture was poured into benzene (50 mL) and washed with water and sodium bicarbonate solution. The organic layer was dried ($MgSO_4$) and evaporated to give an oil that was chromatographed on silica gel (5:1 hexane–ether) yielding the desired cyclohexadiene compound (216 mg, 85%): ^{1}H NMR (CCl_4) δ 2.15 (s, 3 H, CH_3CO), 2.32 (br s, 4 H, CH_2CH_2), 3.48 (s, 2 H, CH_2S), 5.65 (d, 1 H, CH=C, J = 5 Hz), 6.52 (d, 1 H, CH=CCO, J = 5 Hz), and 7.10 (br s, 5 H, Ph).

Method B. To a methanol solution (10 mL) of MeONa (1.08 mmol) was added **11c** (150 mg, 0.54 mmol) at 0 °C and the mixture was stirred for 1 h at room temperature. Then the reaction mixture was diluted with benzene and washed with water and sodium bicarbonate solution. Drying ($MgSO_4$) and evaporation yielded an oil that was chromatographed on a silica gel column to give the desired cyclohexadiene compound (74 mg, 67%) and unreacted *exo*-**11c** (45 mg, 30%).

Acknowledgment. This work was supported in part by the Grant-in-Aid for Scientific Research from the Ministry of Education, Science, and Culture of Japan (No. 58740239).

Registry No. (*E*)-**2a**, 91228-15-8; (*Z*)-**2a**, 91228-16-9; (*E*)-**2b**, 91237-76-2; (*Z*)-**2b**, 91237-77-3; (*E*)-**2c**, 91228-17-0; (*E*)-**2d**, 91228-18-1; (*E*)-**3a**, 86531-05-7; (*Z*)-**3a**, 86531-33-1; (*E*)-**3b**, 86531-06-8; (*Z*)-**3b**, 86531-34-2; (*E*)-**3c**, 86531-07-9; (*Z*)-**3c**, 86531-35-3; (*E*)-**3d**, 86531-08-0; (*Z*)-**3d**, 86531-36-4; **4** (R_1 = C_5H_{11}), 4125-23-9; **4** (R_1 = Me), 78-85-3; **5** (R_2 = Me), 20763-19-3; **5** (R_2 = ME), 91228-19-2; **6** (R_3 = ME), 628-82-0; **6** (R_3 = $PhSCH_2CH_2$), 91228-20-5; **6** (R_3 = $PhSeCH_2CH_2$), 91228-21-6; **7**, 29219-35-0; **8a**, 57432-86-7; **8b**, 19157-14-3; **9a**, 86531-03-5; **9b**, 86531-04-6; **10a**, 5535-48-8; **10b**, 78-94-4; **10c**, 96-33-3; **10d**, 24903-94-4; *endo*-**11a**, 91228-22-7; *exo*-**11a**, 91228-23-8; *endo*-**11b**, 91228-24-9; *exo*-**11b**, 91228-25-0; *endo*-**11c**, 91228-26-1; *exo*-**11c**, 91228-27-2; *endo*-**11d**, 91228-28-3; *exo*-**11d**, 91228-29-4; *endo*-**11e**, 91228-30-7; *exo*-**11e**, 91228-31-8; *endo*-**11f**, 86531-09-1; *exo*-**11f**, 86531-10-4; *endo*-**11g**, 86531-11-5; *exo*-**11g**, 86531-12-6; *endo*-**11h**, 91228-32-9; *exo*-**11h**, 91228-33-0; *endo*-**11i**, 86531-15-9; *exo*-**11i**, 86531-16-0; *endo*-**11j**, 86531-17-1; *exo*-**11j**, 86531-18-2; *endo*-**11k**, 86531-19-3; *exo*-**11k**, 86531-20-6; *endo*-**11l**, 86531-21-7; *exo*-**11l**, 86531-22-8; *endo*-**11m**, 86531-27-3; *exo*-**11m**, 86531-28-4; *endo*-**11n**, 86531-29-5; *exo*-**11n**, 86544-08-3; *endo*-**11p**, 91228-34-1; *exo*-**11p**, 91228-35-2; **12** (X = SPh, Y = Ac), 86531-30-8; **12** (X = OH, Y = Ac), 86531-31-9; **12** (X = H, Y = Ac), 24243-12-7; **12** (X = H, Y = $COCH_2CH_2CH$=$C(CH_3)_2$), 64504-55-8; **12** (X = OH, Y = CO_2Me), 86531-32-0; **12** (X = OH, Y = SO_2Ph), 91228-36-3; **14**, 91228-37-4; **15**, 91228-38-5; MeOCOC≡CCOOMe, 762-42-5.

Supplementary Material Available: Full NMR and analytical data for **11a–o** (2 pages). Ordering information is given on any current masthead page.

The sp^3-Carbon-Attached Trimethylsilyl Group as Removable Asymmetry-Inducing Auxiliary. 1. Aromatic Resin Acid Ring Systems

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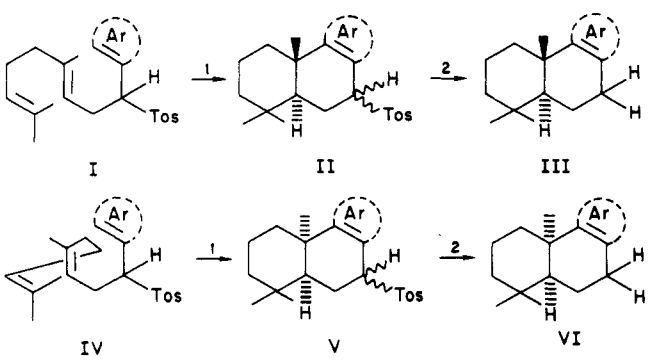
The use of the trimethylsilyl (Me_3Si) unit as detachable diastereoselectivity-inducing auxiliary during cationic polycyclization reactions has been examined. Model studies show **2a,b** to be easily cyclized to **3a–c** in CF_3COOH-containing CH_2Cl_2. Polycyclization of **5a**, on treatment with $SnCl_4$ in CH_2Cl_2, gives a 85:15 ratio of **6a**/**7a**. The same conditions transform **5b** into 5% of 100% diastereoselectively ortho-cyclized **6b** and 46% of para-cyclized **6c**/**7c**, occurring as a 77:23 epimeric mixture. Desilylation of the cyclized materials, using KO-*t*-Bu/Me_2SO, provides **4a–c** and **8a,c**.

Recent work from our laboratories demonstrated a biomimetically modeled entry into aromatic resin acid frameworks III and VI, involving cationic polycyclization of I and IV and Dibal-H mediated detosylation of the obtained systems II and V (Scheme I).[1] The cyclization proceeded, like all concerted polyene cyclizations,[2] stereospecifically, giving either entirely trans- or cis-fused II and V from the preceding *trans*- or *cis*-alkenes I and IV, respectively. Each process produced hereby unequal amounts of tosyl isomers differing configurationally about the epimeric center in product ratios of 60:40 for II and 70:30 for V. The preponderance lay clearly in favor of isomers with the tosyl group occupying positions least impeded by unfavorable 1,3-interactions and reflect an early attainment of product-like transition states, avoiding the development of energetically unpromising species.

Scheme I[a]



[a] 1, FSO_3H-SO_2; 2, Dibal-H.

The principles underlying asymmetric synthesis have found extensive application in steroid strategies[3] where,

(1) Janssen, C. G. M.; Godefroi, E. F. *J. Org. Chem.* **1982**, *47*, 3274.
(2) van Tamelen, E. E. *Acc. Chem. Res.* **1968**, *1*, 111; **1975**, *8*, 152.

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