epimerization of C-3 and therefore cause **1** and **2** to lose their stereochemical identity. We have measured the metastable peak intensities for loss of DO_2CCH_3 and HO_2CCH_3 from **1** and **2** and find no difference.[33] This result suggests that a scrambling mechanism is effectively competing with acetic acid loss under the conditions for metastable ion formation in the electron-impact mass spectrometer.[33] Scrambling competition should increase as the energy decreases, and therefore the rise in the microscopic channel ratios (k_a/k_b) with decreasing energy (Figure 8, Table IV) suggests that such a process is not intervening here. Nevertheless we have no firm evidence to totally exclude a mechanism which may partially interconvert **1** and **2**, and therefore the RRKM derived values of ΔE_{oab} which best match our experimental results must be taken at present, as minimum values.[35] Note the contrast, that in the thermal reaction of the neutral molecule[2] the fact that each diastereotopic deuterium is incorporated specifically into one stereoisomeric 2-butene[6] does not allow any intermediate states which mix the paths to *cis*- and *trans*-2-butene from **1** and **2**.

The literature concerned with the mechanism of the compared ion and thermal reaction for acetic acid loss from 2-butyl acetate[2,30] suggests that these processes share the essential transition-state features of proximity between the C-3 hydrogen and the acetyl carbonyl oxygen and the absence of double-bond character between C-2 and C-3. The resulting necessary conformational states would cause, in both the ion and the thermal reaction, a methyl methyl and a hydrogen hydrogen eclipsing strain in the loss of H_b, i.e., the cis pathway (k_b), and two methyl hydrogen eclipsing interactions leading to loss of H_a, i.e., the trans pathway (k_a). It follows from these considerations that the steric energy difference between the pathways for loss of the C-3 diastereotopic hydrogens should be similar, as we find here, in the compared ion and thermal reactions.[36]

Experimental Section

The C-3 deuterated racemic diastereomers of 2-butyl acetate (**1** and **2**) were prepared as described.[6,8] The C-3 dideuterio-2-butyl acetate (**3**) was prepared by reduction of acetic acid to 1,1-dideuterioethanol, conversion to 1,1-dideuterioethyl bromide, and Grignard reaction with acetyldehyde. The resulting 3,3-dideuterio-2-butanol was esterified with acetic anhydride and collected by preparative gas chromatography. The three deuterated materials were by gas chromatography identical with each other and with 2-butyl acetate standard and were at least 99% homogenious.

The coincidence experiments were conducted on the PEPICO and TPEPICO instruments which have been described.[15,16]

The calculations were carried out on an IBM System 360 Model 65 computer, and the programs are available from R.J.M.

Acknowledgment. Work at the Polytechnic Institute and Clarkson College was financially supported by grants from the National Institutes of Health General Medical Sciences and the donors of the Petroleum Research Fund, administered by the American Chemical Society, to whom we are grateful. Work at the Physikalisch Chemisches Institut has been supported by the Schweizerischer Nationalfounds zur Förderung der Wissenschaftlichen Forschung, Part C-17 of Project No. 2.212-0.79. Financial support by Ciba-Geigy SA, Hoffman-LaRoche & Cie SA, and Sandoz SA, Basel, is gratefully acknowledged. We are indebted to Drs. H. Rosenstock, A. Parr, R. Stockbauer, and E. White V. for their help with experiments conducted on equipment at the National Bureau of Standards and to Professor Tomas Baer for helpful comments.

Registry No. (±)**1**, 56552-75-1; (±)**2**, 56552-76-2; **3**, 80846-06-6; 2-butyl acetate ion, 80846-07-7; 2-butyl acetate, 105-46-4; acetic acid, 64-19-7.

(33) Unpublished data taken by Dr. E. White V. at the National Bureau of Standards, Washington, D.C., in the field free region of a Varian Finnigan MAT731 mass spectrometer.

(34) The stereoselectivity for the normal electron-impact produced ions increases with decreased temperature at about 70 eV and near the ionization threshold[13] and therefore offers no evidence of scrambling. Similar high specificity has been found by R. N. Rej, E. Bacon, and G. Eadon, *J. Am. Chem. Soc.*, **101**, 1668 (1979). There is precedence for nonspecificity in elimination reactions to intervene in metastable but not normal ions. See: P. J. Derrick, J. L. Holmes, and R. P. Morgan, *ibid.*, **97**, 4936 (1975) and references therein.

(35) Increasing the lifetime and/or decreasing the energy of the *m/e* 56 producing molecular ions in the coincidence spectrometer to find where k_a/k_b falls back toward unity could be one way of detecting the onset of stereochemical scrambling.

(36) This work further supports the utility of stereochemical observations for relating gas phase ion chemistry and the chemistry of thermalized molecules as discussed in: M. M. Green, *Tetrahedron*, **36**, 2687 (1980), Report No. 95.

Stereochemical Aspects of the Intramolecular Diels–Alder Reactions of Deca-2,7,9-trienoate Esters. 3. Thermal, Lewis Acid Catalyzed, and Asymmetric Cyclizations

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Abstract: Stereochemical aspects of the intramolecular Diels–Alder reactions of a series of deca-2,7,9-trienoate esters are described. The thermal cyclizations of trienes **4–8** afforded mixtures of cycloadducts, among which the trans-fused products predominated. The product selectivity in these cases was independent of dienophile stereochemistry. The structures of the cycloadducts were established by chemical methods, including product interconversions, degradations, and independent synthesis. The cyclizations of **5–8** were catalyzed by a number of Lewis acids, of which ethylaluminum dichloride, diethylaluminum chloride, and (menthyloxy)aluminum dichloride were particularly effective. The Lewis acid catalyzed cyclizations of **5** and **7** afforded trans-fused products, exclusively, in excellent yield, whereas the catalyzed cyclizations of **6** and **8** afforded mixtures of cycloadducts in poor yield. The catalyzed cyclizations of chiral triene esters **61** and **62** afforded mixtures of trans-fused diastereomeric products, the diastereomeric excess (corresponding to enantiomeric excess) of which, in most cases, ranged from 30% (for **61**) to 64% (for **62**).

The intramolecular Diels–Alder reaction promises to become widely used in the synthesis of natural products.[1] The reaction has been used to synthesize a number of interesting ring systems and has already been applied to a variety of problems in natural

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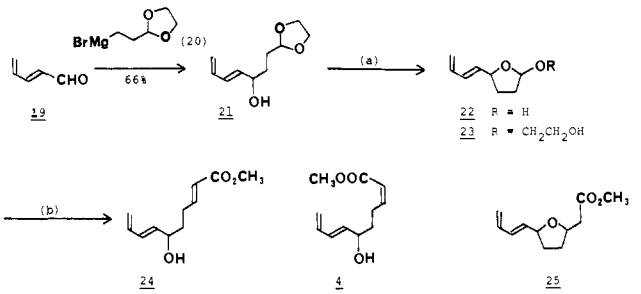
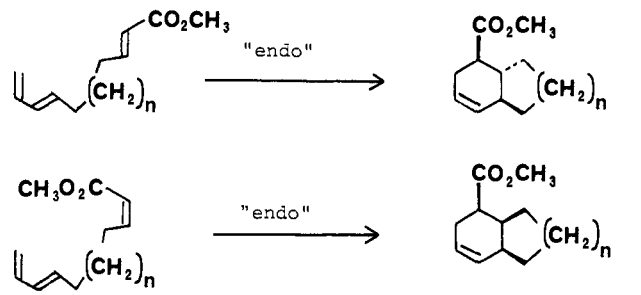
Scheme I



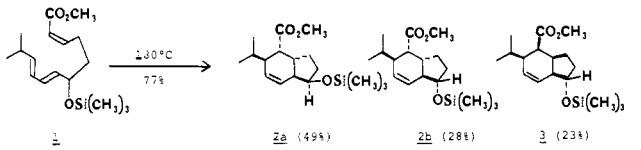
(a) H_3O^+; (b) $(C_6H_5)_3PCHCOOCH_3$, CH_3OH (13% of **4**, 22% of **24**, 36% of **25**, and 18% of **23** for two steps from **21**; 78% of **24** and 6% of **4** from **22** in CH_2Cl_2

products chemistry.[2] In order for this reaction to become accepted as a standard synthetic transformation, however, the stereochemical features must be well-defined, and (ideally) the reactions must be highly selective. Although a number of stereochemical studies of the intramolecular Diels–Alder reaction have been reported,[3] these two criteria are not yet fully satisfied.

We have been interested in using intramolecular Diels–Alder reactions in natural product synthesis since 1974 when we initiated our studies on the total synthesis of dendrobine.[4] At that time little was known about the stereochemistry of the cyclizations of trienes bearing terminal dienophile activating groups. From the outset, we assumed that dienophile geometry would dictate ring fusion stereochemistry in the reaction products.

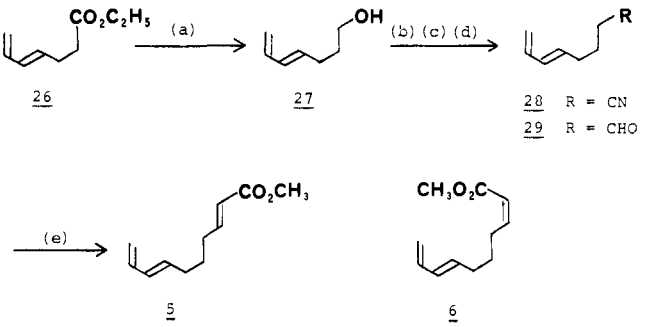


Unexpectedly, however, we discovered that cis-triene **1** cyclized



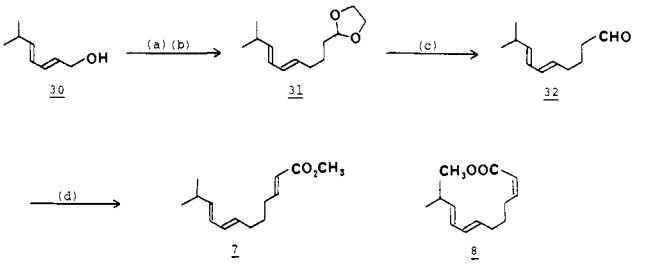
preferentially to trans-fused **2a** and **2b**, products of exo-Diels–Alder

Scheme II



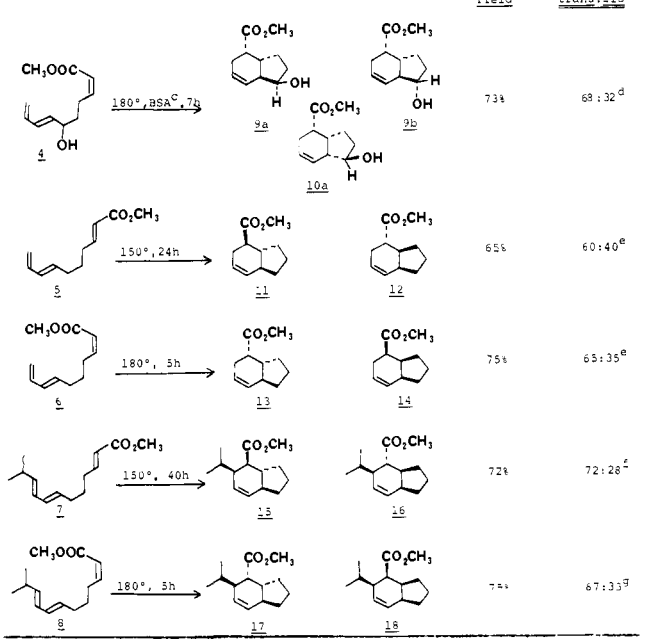
(a) $LiAlH_4$, Et_2O, 0 °C (79%); (b) CH_3SO_2Cl, Et_3N, CH_2Cl_2, 0 °C; (c) KCN, EtOH (20% H_2O), reflux (77% from **27**); (d) DIBAL, Et_2O, 0 °C; (e) $(C_6H_5)_3PCHCOOCH_3$ (47–60% of **5** and 4–5% of **6** from **28** in CH_2Cl_2; 35–42% of **5** and 18–19% of **6** in CH_3OH)

Scheme III



(a) Ac_2O, py (80%); (b) Li_2CuCl_4, **20**, THF, −10 °C (65–70%); (c) THF, H_2O, HOAc (92–100%); (d) $(C_6H_5)_3PCHCOOCH_3$ (43–48% of **7** and 23–28% of **8** in CH_3OH; 79% of **7** and 6% of **8** in CH_2Cl_2)

Table I



	Yield[a]	trans:cis[b]
4 → **9a**, **9b**, **10a** (180°, BSA[c], 7h)	73%	68:32[d]
5 → **11**, **12** (150°, 24h)	65%	60:40[e]
6 → **13**, **14** (180°, 5h)	75%	65:35[e]
7 → **15**, **16** (150°, 40h)	72%	72:28[f]
8 → **17**, **18** (180°, 5h)	75%	67:33[g]

[a] Total yield of chromatographed products. [b] Ratio of trans-fused to cis-fused products. [c] Bis(trimethylsilyl)acetamide; products were isolated after acid hydrolysis. [d] GC analysis performed on the Me_3Si ethers using a 10-ft 4% Zonyl E-7/Chromosorb G column at 150 °C. [e] GC analysis performed on a 10-ft 4% SE-30 Chromosorb G column at 125 °C. [f] Inseparable by tlc or GC; product ratio assigned by NMR. [g] GC analysis performed at 150 °C on the column described in *e*.

reactions.[5] This result prompted us to investigate the stereochemistry of the intramolecular Diels–Alder reactions of a series

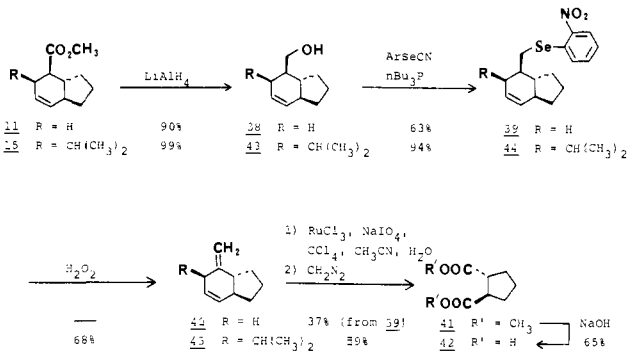
(1) Reviews: (a) Brieger, G.; Bennett, J. N. *Chem. Rev.* **1980**, *80*, 63. (b) Oppolzer, W. *Synthesis* **1978**, 793. (c) Oppolzer, W. *Angew. Chem., Int. Ed. Engl.* **1977**, *16*, 10; (d) Funk, R. L.; Vollhardt, K. P. C. *Chem. Soc. Rev.* **1980**, *9*, 41. (e) Carlson, R. G. *Annu. Rep. Med. Chem.* **1974**, *9*, 270.

(2) A few recent examples: (a) Snowden, R. L. *Tetrahedron Lett.* **1981**, *22*, 97, 101. (b) Boeckman, R. K., Jr.; Ko, S. S. *J. Am. Chem. Soc.* **1980**, *102*, 7146. (c) Wilson, S. R.; Misra, R. N. *J. Org. Chem.* **1980**, *45*, 5079. (d) Ichihara, A.; Kimura, R.; Yamada, S.; Sakamura, S. *J. Am. Chem. Soc.* **1980**, *102*, 6353. (e) Pyne, S. G.; Hensel, M. J.; Byrn, S. R.; McKenzie, A. T.; Fuchs, P. L. *Ibid.* **1980**, *102*, 5960. (f) Martin, S. F.; Tu, C.; Chou, T. *Ibid.* **1980**, *102*, 5274. (g) Taber, D. F.; Saleh, S. A. *Ibid.* **1980**, *102*, 5085. (h) Schmitthenner, H. F.; Weinreb, S. M. *J. Org. Chem.* **1980**, *45*, 3372. (i) Roush, W. R.; Gillis, H. R. *Ibid.* **1980**, *45*, 4283. (j) Tietze, L.-F.; Kiedrowski, G. v. *Tetrahedron Lett.* **1981**, *22*, 219. (k) Schmidlin, T.; Zürcher, W.; Tamm, C. *Helv. Chim. Acta* **1981**, *64*, 235.

(3) (a) White, J. D.; Sheldon, B. G. *J. Org. Chem.* **1981**, *46*, 2273. (b) Nader, B.; Franck, R. W.; Weinreb, S. M. *J. Am. Chem. Soc.* **1980**, *102*, 1153. (c) Parker, K. A.; Adamchuk, M. R. *Tetrahedron Lett.* **1978**, 1689. (d) Oppolzer, W.; Frostl, W. *Helv. Chim. Acta* **1975**, *58*, 590. (e) Oppolzer, W. *Tetrahedron Lett.* **1974**, 1001. (f) Oppolzer, W.; Keller, K. *J. Am. Chem. Soc.* **1971**, *93*, 3836. (g) Gschwend, H. W.; Lee, A. O.; Meier, H.-P. *J. Org. Chem.* **1973**, *38*, 2169. (h) Gschwend, H. W.; Meier, H.-P. *Angew. Chem.* **1972**, *84*, 291. (i) House, H. O.; Cronin, T. H. *J. Org. Chem.* **1965**, *30*, 1061. (j) Boeckman, R. K., Jr.; Ko, S. S. *J. Am. Chem. Soc.*, in press.

(4) Roush, W. R. *J. Am. Chem. Soc.* **1980**, *102*, 1390; *1978*, **100**, 3599.

Scheme IV



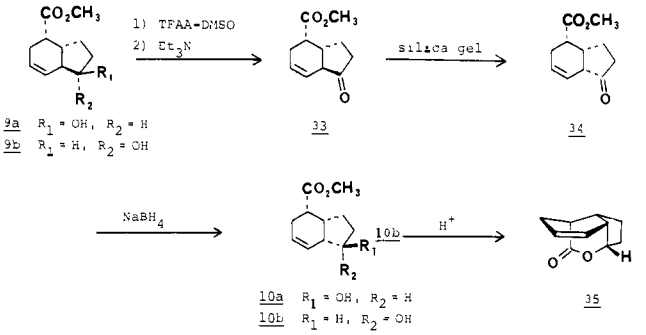
of substituted methyl deca-2,7,9-trienoates[6] and, subsequently, of methyl undeca-2,8,10-trienoates.[7] We describe herein the full details of our study of the thermal and Lewis acid catalyzed cyclizations of methyl deca-2,7,9-trienoates, preliminary accounts of which have been previously reported.[6a,b] We also describe the results of our initial studies of asymmetric intramolecular Diels–Alder reactions.

Results and Discussion

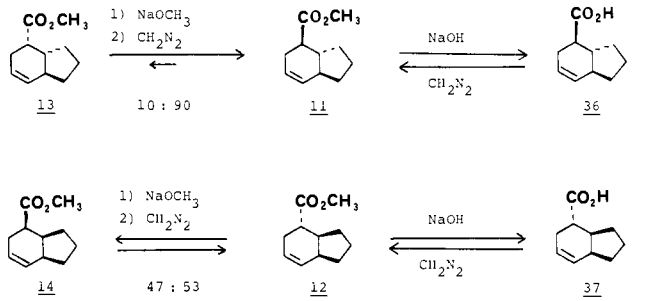
Thermal Cyclizations. Trienes **4–8** were synthesized by the routes summarized in Schemes I–III.[8] These sequences were designed to provide rapid access to both dienophile isomers of each structural series.[9] These routes proved to be highly selective for all-trans trienes **24**, **5**, and **7** if the stabilized Wittig reactions were performed in CH_2Cl_2. When these Wittig reactions were performed in CH_3OH, approximate 65:35 mixtures of olefin isomers were produced.[10] In all cases, these mixtures were easily separated by silica gel chromatography.

The results of the thermal cyclizations of **4–8** are summarized in Table I.[11] Stereochemistry was assigned to the individual cycloadducts primarily by chemical methods, as discussed below.

Oxidation of either **9a** or **9b** with the reagent prepared from Me_2SO and TFAA followed by Et_3N[12] afforded a crude, unstable ketone **33** which upon silica gel chromatography isomerized to the more stable cis-fused isomer **34**.[4,13] Reduction of **34** with $NaBH_4$ in EtOH afforded a separable mixture of **10a** (4%) and **10b** (60%), the latter of which lactonized to **35** (79%) on treatment with *p*-TsOH in refluxing benzene. Thus, **9a** and **9b** have trans ring fusions.

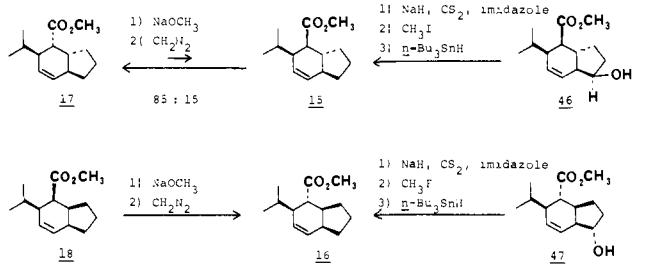


Cycloadducts **11** and **12** were converted to the known acids **36** and **37** by alkaline hydrolysis.[3i] Epimerization of **13** with $NaOCH_3$



in CH_3OH (80 °C) followed by diazomethane esterification afforded a 90:10 mixture of **11** and **13**. Similarly, **14** and **12** were correlated by ester epimerization. An independent confirmation of the ring-fusion stereochemistry of **11** (and hence also **13**) was provided by degradation of **11** to *trans*-cyclopentane-1,2-dicarboxylic acid (**42**), mp 157–160 °C (lit.[14] mp 160–161 °C), as outlined in Scheme IV. A similar sequence was used to degrade **15** to **42**. These sequences proved to be extremely useful in determining the absolute configurations of optically active **38** and **43** (vide infra). It is important to note that it is the degradations performed on the optically active intermediates, and not on the racemates, which provides unequivocal confirmation of ring fusion stereochemistry in these cases.

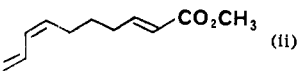
The structures of cycloadducts **15** and **16** were further con-



firmed by independent synthesis from the known[4] alcohols **46** and **47** using Barton's method of deoxygenation.[15] Cycloadducts **17** and **18** were correlated with **15** and **16** by ester epimerization. It is interesting to note that even under equilibrating conditions, the carbomethoxy group of the epimeric pair **15–17** prefers to occupy an axial position in **17**. Comparison of this result to the equilibrium value of 90:10 for **11–13** leads one to the conclusion that the gauche interaction between the equatorial carbomethoxy group and the pseudoaxial isopropyl group in **15** is destabilizing by approximately 2.8 kcal mol^{-1}.[16]

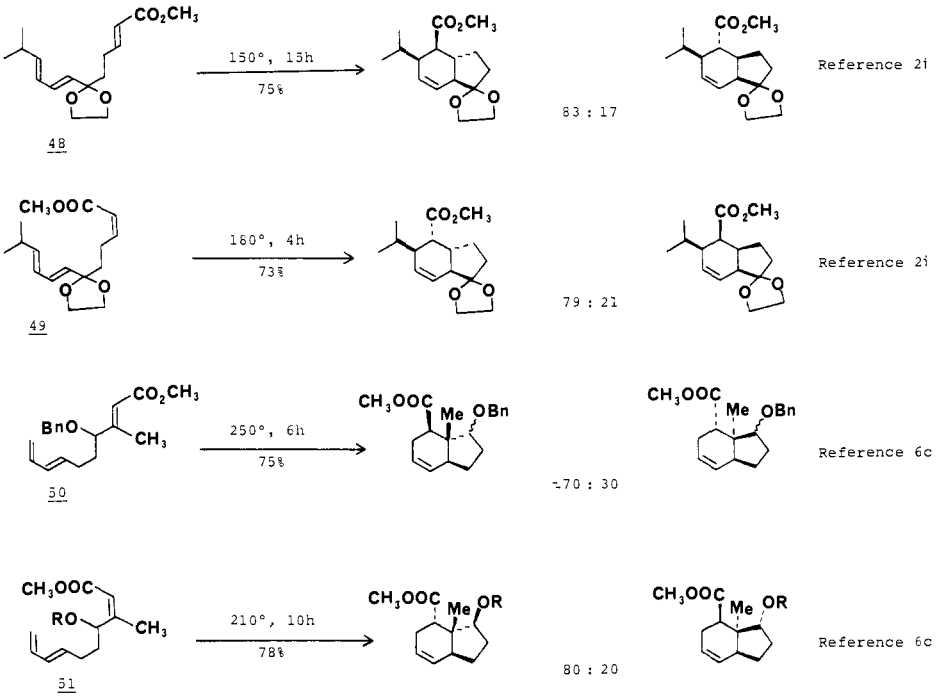
It is apparent from the results summarized above that the major products of the Diels–Alder reactions of **4–8** possess trans ring

(5) Roush, W. R. *J. Org. Chem.* **1979**, *44*, 4008.
(6) (a) Roush, W. R.; Ko, A. I.; Gillis, H. R. *J. Org. Chem.* **1980**, *45*, 4264. (b) Roush, W. R.; Gillis, H. R. *Ibid.* **1980**, *45*, 4267. (c) Roush, W. R.; Peseckis, S. M. *J. Am. Chem. Soc.* **1981**, *103*, 6696. (d) See also ref 2i.
(7) Roush, W. R.; Hall, S. E. *J. Am. Chem. Soc.* **1981**, 103, 5200.
(8) The synthesis and stereochemical study of **4** was performed by W.R.R. during a postdoctoral stay at Harvard University (1978). W.R.R. gratefully acknowledges the generous financial assistance provided by the late Professor R. B. Woodward (NIH Grant 5 R01 GM04229) for this phase of these studies.
(9) We originally planned to study the Diels–Alder reactions of both **4** and **24**, which were synthesized as outlined in Scheme I. The Me_3Si ether of **24** was prepared and cyclized, but the mixture of at least three (possibly four) cycloadducts proved to be inseparable by TLC, GC, and preparative LC. Studies of this system, therefore, were abandoned.
(10) House, H. O.; Jones, V. K.; Frank, G. A. *J. Org. Chem.* **1964**, *29*, 3327.
(11) The intramolecular Diels–Alder reaction of **5** was previously studied by House and Cronin.[3i] These authors found that a *mixture* of **5** and **ii** (ratio unknown) cyclized to a mixture of **11** and **12** and that isomerically pure **ii** cyclized exclusively to **12**. It was assumed that **11** was the sole cycloadduct



of **5** even though the amount of degenerate, exo cyclization of **5** to **12** could not be determined. Our results clearly show that the cyclization of **5**, in fact, affords a 60:40 mixture of **11** and **12**.
(12) Omura, K.; Sharma, A. K.; Swern, D. *J. Org. Chem.* **1976**, *41*, 957.
(13) House, H. O.; Rasmusson, G. H. *J. Org. Chem.* **1963**, *28*, 31.
(14) Fuson, R. C.; Fleming, C. L.; Warfield, P. F.; Wolf, D. E. *J. Org. Chem.* **1945**, *10*, 121.
(15) Barton, D. H. R.; McCombie, S. W. *J. Chem. Soc., Perkin Trans. 1* **1975**, 1574.
(16) Aycard, J. P.; Bodot, H. *Can. J. Chem.* **1973**, *51*, 741; *Org. Magn. Reson.* **1975**, *7*, 226.

Table II



fusions. Clearly, the endo rule fails to predict the outcome of the cyclizations of **4**, **6**, and **8**.[17] Moreover, the product distribution appears to be virtually independent of dienophile stereochemistry (compare **5** vs. **6** and **7** vs. **8**), which implies that secondary orbital interactions are not primarily involved in determining the outcome of the cyclizations of all-trans trienes **5** and **7**. To the extent that secondary orbital interactions stabilize an endo transition state, one expects to observe relatively more trans-fused product from the (*E*,*E*)-trienes and relatively more cis-fused product from the (*Z*,*E*)-trienes. This tendency is not apparent in the data. In particular, **6** affords slightly more trans-fused product than does **5**. The lack of secondary orbital control and the failure of the endo rule in these cases is not surprising, however, since studies of Diels–Alder reactions of acyclic dienes and dienophiles have shown that this rule is well obeyed only at low temperatures and that many violations are known.[18]

It is immediately apparent that each of these cyclizations occurs preferentially via transition-state A, in which the three-carbon

A B

endo-1,11 R_1 = $COOCH_3$, R_2 = H exo-1,11

exo-8,12 R_1 = H, R_2 = $COOCH_3$ endo-8,12

bridge adopts an exo position relative to the diene. We originally suggested that this orientation was preferred as a consequence of strain and nonbonded interactions involving the atoms on the chain linking the diene and dienophile which destabilize B relative to A.[5,6a] The major nonbonded interaction results from the proximal approach of the C_4-methylene to C_8-H in transition-state B, an interaction which is absent in A. The effect of transition-state strain is more subtle and is apparent by Dreiding model analysis only if one moves the dienophile, along the reaction coordinate, from a position directly above the diene to the position occupied by the dienophile carbon atoms in the boat conformation of the product cyclohexene. This transition-state trajectory has been predicted by calculations.[19] This method of model analysis led us to conclude that bonding geometries are more easily attained in transition-state A than in B.

Recently, however, Boeckman,[2b] White,[3a] and their respective co-workers have independently suggested that Diels–Alder reactions of this type occur by unsymmetrical but concerted transition states in which bond formation between one pair of carbon atoms precedes bond formation at the other termini. In the cases of **4–8** (Table I), one would predict that bond formation between carbons 3 and 7 should be initiated first, since the coeffieicnt of the LUMO at C_3 should be greater than the coefficient at C_2.[20] Under these circumstances, nonbonded interactions involving the atoms on the chain separating the diene and dienophile are expected to develop at an early stage of the reaction, as the five-membered ring is forming, and to become a dominant factor in the course of the reaction.[2b,3a]

Both of these rationales lead to the same conclusions regarding the cyclizations of terminally activated decatrienoates (Table I). It should be noted, however, that our original transition-state model fails to account for the cyclizations of certain perhydroindene precursors which lack *terminal* dienophile activation.[6c] These exceptional cases have been rationalized in terms of the non-synchronous transition-state model. It is, of course, unwise to overinterpret results such as those presented in Table I, for which the product distributions are governed by only ~0.5–0.8 kcal mol^{-1} differences in transition-state energy.[17] It is sufficient to point out that these cyclizations are selective for the trans-fused product and that the aforementioned rationale are consistent with the observed results, as well as with cases previously reported.[2b,3a,4,5] Although the selectivity for the trans-fused product is slight for **4–8**, more hghly functionalized 2,7,9-trienoates are frequently more selective; a few representative examples are listed in Table II. These data indicate that substituent effects may also be

(17) Control experiments established that each of the cyclizations reported in Table I is a kinetically controlled process.

(18) Reviews of the Diels–Alder reaction: (a) Sauer, J.; Sustmann, R. *Angew. Chem., Int. Ed. Engl.* **1980**, *19*, 779. (b) Sauer, J. *Ibid.* **1967**, *6*, 16. (c) Wollweber, H. "Diels-Alder Reakton"; Georg Thieme Verlag: Stuttgart, 1972. (d) Onishenko, A. S. "Diene Synthesis" (English Translation); Israel Program for Scientific Translation: Jerusalem, 1964, and references therein.

(19) (a) Kikuchi, O. *Tetrahedron* **1971**, *27*, 2791. (b) McIver, J. W., Jr. *Acc. Chem. Res.* **1974**, *7*, 72. (c) Townshend, R. E.; Ramunni, G.; Segal, G.; Hehre, W. J.; Salem, L. *J. Am. Chem. Soc.* **1976**, *98*, 2190.

(20) Houk, K. N. *J. Am. Chem. Soc.* **1973**, *95*, 4092.

Table III

entry	substrate	catalyst, conditions, yield[a]	products	ratio[b]
1	7	(menthyloxy)$AlCl_2$[c] (1.4 equiv), 23 °C, 48 h, 79–83%	15-16	100:0[d]
2	7	$EtAlCl_2$ (0.9 equiv), 23 °C, 18 h, 70%	15-16	100:0[d]
3	7	(1.1 equiv), 23 °C, 12 h, 47%	15-16	100:0[e]
4	7	Et_2AlCl (1.3 equiv), 23 °C, 48 h, 77–85%	15-16	100:0[e]
5	7	$AlCl_3$ (0.1 equiv), 23 °C, 18 h, 75–84%	15-16	100:0[d]
6	7	(0.5 equiv), 23 °C, 7 h, 55%	15-16	100:0[e]
7	7	$BF_3 \cdot Et_2O$ (1.5 equiv), 50 °C, 46 h, 52%	15-16	100:0[e]
8	7	$TiCl_4$ (0.2 equiv), 50 °C, 10 h, 47%	15-16	100:0[e]
9	7	(1.6 equiv), 23 °C, 1 h, 23%	15-16	100:0[e]
10	7	$SnCl_4$ (1.0 equiv), 50 °C, 24 h, 42%	15-16	100:0[e]
11	7	WCl_6 (0.5 equiv), 25 °C, 1 h, 52%	15-16	100:0[e,g]
12	7	$NbCl_5$ (0.4 equiv), 25 °C, 24 h, 56%	15-16	100:0[e,h]
13	5	(menthyloxy)$AlCl_2$[c] (1.3 equiv), 23 °C, 60 h, 72–79%	11-12	100:0[d,f]
14	5	$EtAlCl_2$ (0.9 equiv), 23 °C, 36 h, 60%	11-12	100:0[e]
15	5	(1.1 equiv), 23 °C, 48 h, 34%	11-12	100:0[d,f]
16	5	Et_2AlCl (0.9 equiv), 23 °C, 43 h, 50%	11-12	100:0[e]
17	5	$AlCl_3$ (0.1 equiv), 50 °C, 10 h, 50%	11-12	100:0[d,f]
18	8	$EtAlCl_2$ (0.9 equiv), 23 °C, 40 h, 59%	17-18	63:37[f]
19	8	$AlCl_3$ (0.1 equiv), 50 °C, 18 h, 48%	17-18	68:32[f]
20	6	$EtAlCl_2$ (1.0 equiv), 23 °C, 40 h, 27%	13-14	52:48[f]
21	6	(menthyloxy)$AlCl_2$[c] (1.0 equiv), 23 °C, 72 h, 20%	13-14	56:44[f]

[a] The yield of isolated (chromatographed) product. [b] Ratio of trans-fused to cis-fused product. [c] Racemic (menthyloxy)$AlCl_2$ was used. [d] Product ratio determined by 250-MHz NMR analysis under conditions with resolution greater than 60:1 signal to noise. Less than 2% of the cis-fused isomer could go undetected under these conditions. [e] Product ratio determined by NMR analysis at either 60 or 90 MHz. As much as 5% of the cis-fused product could go undetected by this method. [f] Product ratio determined by GC analysis (10-ft 4% SE-30/Chromosorb G). [g] Triene 7 was recovered (15%). [h] Triene 7 was recovered (24%).

important in increasing the energy difference between transition states A and B.

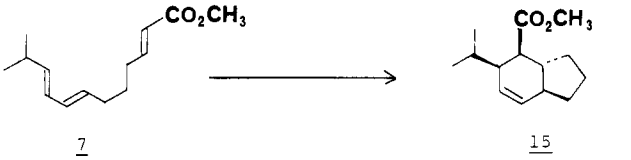
Lewis Acid Catalyzed Cyclizations. It is clear from the foregoing discussion that the thermal decatrienoate cyclizations are not, in general, highly selective. We thus turned to Lewis acid catalysis[21] as a means of improving the endo–exo selectivity of these intramolecular cyclizations.

Only a few examples of catalyzed intramolecular Diels–Alder reactions had been reported prior to this study.[22] The rate accelerations observed in those cases were only modest, and changes in product selectivity had not been observed. We found, however, that trienes **5–8** are subject to catalysis with remarkable rate acceleration (Table III). Whereas the thermal cyclizations of these trienes (Table I) required temperatures of at least 150 °C for a practical rate of cyclization, the catalyzed cyclizations are conveniently performed at temperatures below 50 °C—*in most cases at room temperature*—depending on the Lewis acid employed. In addition, the *catalyzed cyclizations of* ***5*** *and* ***7*** *proved to be highly selective, affording exclusively the trans-fused (endo) cycloadducts* ***11*** *and* ***15****, respectively*. Curiously, trienes **6** and **8**, the cis-dienophile isomers of **5** and **7**, were also subject to catalysis, but significant changes in product selectivity were not observed.

Typically, these cyclizations were performed by adding a Lewis acid to a solution of triene in CCl_4 or CH_2Cl_2 under an inert atmosphere, except for reactions catalyzed by (menthyloxy)aluminum dichloride which were performed in a toluene–CH_2Cl_2 cosolvent mixture.[23] In most cases, stoichiometric quantities of Lewis acid were required for complete cyclization, because the cyclization products apparently formed stronger complexes with the Lewis acids than did the starting triene esters. For example, cyclization of **7** catalyzed by 0.2 equiv of $TiCl_4$ (entry 8, Table III) proceeded to ~20% completion within 1 at room temperature but required heating at 50 °C for 10 h for the reaction to go to completion.

The catalysts used in this study vary widely with respect to rate and yield of cyclization. Diene polymerization competes with cyclization in nearly all of the cases reported in Table III and is responsible for the poor yields reported in many of the entries. This problem is most serious with triene **6** and when classical Lewis acid catalysts such as $BF_3 \cdot Et_2O$, $TiCl_4$, or $SnCl_4$ are used. Polymerization is also a problem with $AlCl_3$ and $EtAlCl_2$ but is minimized by limiting the amount of these reagents employed (entries 2, 3, 5, 6, 14, 15). The best catalysts in terms of product

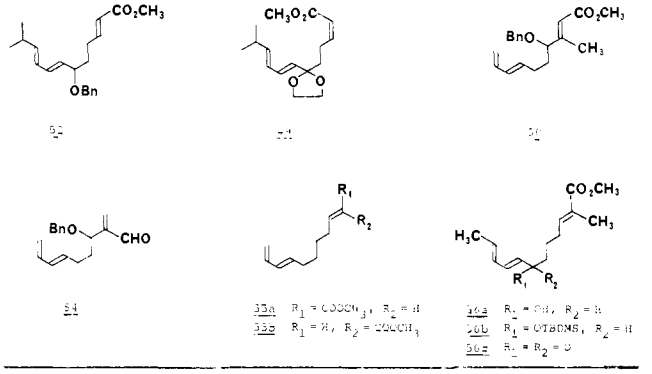
Table IV



7 15

$TiCl_4$	(0.9 equiv), $EtAlCl_2$ (0.1 equiv), 1 h, 23 °C	62%
$TiCl_4$	(0.9 equiv), $EtAlCl_2$ (0.2 equiv), 1 h, 23 °C	72%
$TiCl_4$	(0.9 equiv), Et_2AlCl (0.2 equiv), 12 h, 23 °C	45%
$TiCl_4$	(0.9 equiv), (menthyloxy)$AlCl_2$ (0.1 equiv), 1 h, 23 °C	45%

Table V



(21) (a) Fleming, I. "Frontier Orbitals and Organic Chemical Reactions"; Wiley: New York, 1976; pp 161–165. (b) Houk, K. N.; Strozier, R. W. *J. Am. Chem. Soc.* **1973**, *95*, 4094. (c) Houk, K. N. *Acc. Chem. Res.* **1975**, *8*, 361.

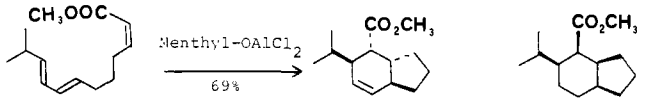
(22) (a) Wenkert, E.; Naemura, K. *Synth. Commun.* **1973**, *3*, 45; (b) Vig, O. P.; Trehan, I. R.; Kumar, R. *Indian J. Chem.* **1977**, *15B*, 319. (c) DeClercq, P. J.; Van Royen, L. A. *Ibid.* **1979**, *9*, 771. (d) Mukaiyama, T.; Tsuji, T.; Iwasawa, N. *Chem. Lett.* **1979**, 697. See also: Mukaiyama, T.; Iwasawa, N.; Tsuji, T.; Narasaka, K. *Ibid.* **1979**, 1175. (e) Snider, B. B.; Duncia, J. V. *J. Org. Chem.* **1980**, *45*, 3461. (f) Two other cases were reported after this manuscript was submitted for publication: Stork, G.; Clark, G.; Shiner, C. S. *J. Am. Chem. Soc.* **1981**, *103*, 4948. Funk, R. L.; Zeller, W. E. *J. Org. Chem.* **1982**, *47*, 180.

(23) The $AlCl_3$-catalyzed cyclizations of **7** and **8** performed in toluene gave poor results owing to Friedel–Crafts reaction with the solvent.

yield are (menthyloxy)aluminum dichloride,[24] ethylaluminum dichloride, and diethylaluminum chloride.[25] These reagents are mild (one exception is noted below), and the rate of cyclization is relatively slow. On the other hand, $TiCl_4$ effects the fastest cyclization but is the least efficient reagent in terms of product yield (entry 9, polymerization is a serious problem in this case). We have found, however, that $TiCl_4$-promoted diene polymerization can be suppressed if the reaction is doped with small amounts of alkoxy- or alkylaluminum halides (Table IV).[26] We note also the first applications of WCl_6 and $NbCl_5$ as catalysts for Diels–Alder reactions (Table III, entries 11, 12).

The product distribution data summarized in Table III do not appear to be the consequence of selective decomposition of any of the observed or potential cycloadducts. Control experiments established that mixtures of **11** and **12**, **13** and **14**, **15** and **16**, and **17** and **18** are stable toward $EtAlCl_2$ under the conditions reported in Table III. Product instability, however, was observed in two cases; both involved the product mixtures obtained from **8**.

The first involved an $AlCl_3$ (0.1 equiv) catalyzed cyclization of **8** which was allowed to proceed for 13 days at room temperature. This experiment afforded 21% of a 9:1 mixture of **17** and **18**, the expected products, together with 14% of a 55:45 mixture of **15**, the ester epimer of **17**, and **52**, the dihydro derivative of **18**. The two latter products were not observed under the conditions reported in entry 19 of Table III. Dihydro compound **52** was also obtained from the (menthyloxy)aluminum dichloride catalyzed cyclization of **8**; cycloadduct **18** was not observed in this case. The



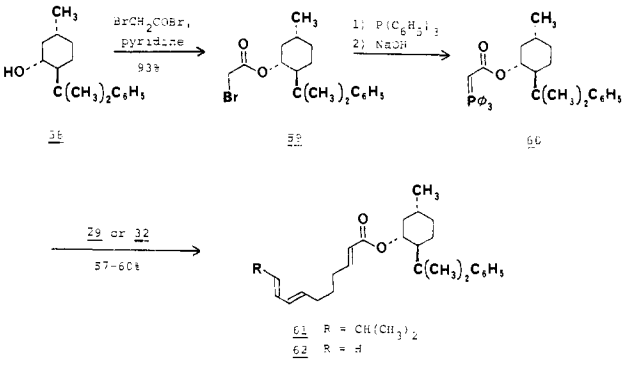
8 17 52

mechanism of formation of **52** remains unceratin at present but presumably represents a special case because we have not observed reduction of any of the other cycloadducts by (menthyloxy)aluminum dichloride. In no other cases have we suspected that products are unstable under the cyclization conditions.

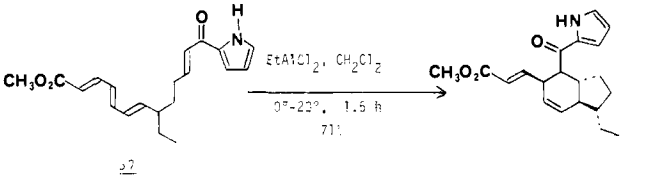
It is clear from the data tabulated in Tables I and III that the cyclizations of all-trans trienes **5** and **7** are significantly improved by using Lewis acid catalysis but that the cyclizations of cis-trienes **6** and **8** are not. If one assumes that the increased selectivity realized with **5** and **7** is the consequence of increased secondary orbital control[21] resulting from an interaction between the ester carbonyl group and the Lewis acid, then the results with **6** and **8** must indicate that increased secondary orbital control is insufficient to overcome to any significant extent the transition-state preference for the trans-fused product manifested by the thermal cyclizations. For **5** and **7** the transition-state preference for the trans ring fusion and secondary orbital control reinforce one another; consequently, these cyclizations are highly selective.

In spite of the success realized with **5–8**, the catalytic process is somewhat limited in scope. To date, we have been unable to

Scheme V



catalyze the cyclizations of the trienes listed in Table V.[27] With the exception of **55a** and **55b**, these trienes possess oxygen substituents which presumably complex with the Lewis acids as a prelude to subsequent decomposition reactions. Trienes **49**, **53**, and **56** are very susceptible to pentadienyl carbonium ion formation, a process which is presumed to be involved in the decomposition of these molecules. Our stuudies of **5** and **6** (Table III) have shown that monosubstituted dienes are more susceptible to diene polymerization than are 1,4-disubstituted dienes. This factor is undoubtedly responsible in part for the unsuccessful attempts to catalyze the cyclizations of **50**, **54**, and **55**. We have, however, successfully catalyzed the cyclization of **57**.[28] Methods to extend catalysis to the trienes listed in Table V are under current investigation.



57

Asymmetric Cyclizations. Although considerable effort has been devoted to understanding the stereochemical features of the intramolecular Diels–Alder reaction, only one report has appeared regarding absolute stereochemical induction (asymmetric synthesis) in these reactions.[29] In contrast, asymmetric bimolecular Diels–Alder reactions have been studied in a number of laboratories.[30] These studies have shown that the optical yield of product is greatest when the reaction is performed with Lewis acid catalysis.[30a,b] Chiral catalysts have been used,[24b] but the greatest success has been realized by using chiral substrates. Acrylate esters of 2-(1-methyl-1-phenylethyl)-5-methylcyclohexanol ("phenylmenthol", **58**) have proven to be particularly effective in this regard.[30c,e]

Accordingly, triene esters **61** and **62** were chosen for study. (−)-Phenylmenthol (**58**)[30c] was converted into bromoester **59** under standard conditions. Treatment of **59** with triphenylphosphine

(24) (a) Hayakawa, Y.; Fueno, T.; Furukawa, J. *J. Polym. Sci.* **1967**, *5*, 2099. (b) Hashimoto, S.-I.; Komeshima, N.; Koga, K. *J. Chem. Soc., Chem. Commun.* **1979**, 437.

(25) Alkylaluminum halides have previously been used as catalysts for ene and Diels–Alder reactions; see, for example: Snider, B. B. *Acc. Chem. Res.* **1980**, *13*, 426. Snider, B. B.; Rodini, D. J.; Conn, R. S. E., Sealfon, S. *J. Am. Chem. Soc.* **1979**, *101*, 5283. Oppolzer, W.; Robbiani, C. *Helv. Chim. Acta* **1980**, *63*, 2010. Oppolzer, W.; Robbiani, C.; Bättig, K. *Ibid.* **1980**, *63*, 2015. Miyajima, S.; Inukai, T. *Bull. Chem. Soc. Jpn.* **1972**, *45*, 1553. See also ref 30e.

(26) These experiments were undertaken on the assumption that trace amounts of HCl present in $TiCl_4$ might be causing the olefin polymerization and that the alkoxyaluminum or alkylaluminum reagents might function as acid scavengers. The actual reagents formed under these conditions are probably mixed titanium–aluminum complexes resembling Ziegler–Natta catalysts (see Boor, J. "Ziegler-Natta Catalysts", Academic Press: New York, 1979). The situation is certainly more complicated than we originally supposed; see, for example, entries 1–3 of Table VI for results pertaining to asymmetric induction. Ziegler-type reagents have previously been used as catalysts for Diels–Alder reactions: (a) Robinson, R.; Fray, G. I. British Patent 853 840, 1960; *Chem. Abstr.* **1960**, *54*, 24614i. (b) Lutz, E. F. *J. Org. Chem.* **1963**, *28*, 912.

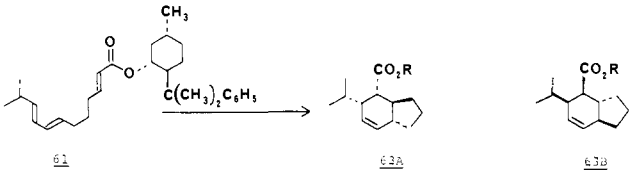
(27) Attempts to catalyze the cyclizations of **50** and **54** were performed by Mr. Steven M. Peseckis,[6c] while attempts to catalyze the cyclizations of **55** and **56** were performed by Mr. Steven E. Hall.[7]

(28) Roush, W. R.; Myers, A. G. *J. Org. Chem.* **1981**, *46*, 1509.

(29) (a) Mukaiyama, T.; Iwasawa, N. *Chem. Lett.* **1981**, *29*. This paper was published after our studies (Table VI) were completed. (b) A number of examples involving *internal relative* asymmetric induction with chiral trienes have also been reported; see, for example: ref 2e, 2j, and 2k and Oppolzer, W.; Flaskamp, E. *Helv. Chim. Acta* **1977**, *60*, 204. See also ref 1 and Quinkert, G.; Schwartz, U.; Stark, H.; Weber, W.-D.; Baier, H.; Adam, F.; Dürner, G. *Angew. Chem., Int. Ed. Engl.* **1980**, *19*, 1029 for examples of optically active syntheses of steroids by routes involving *o*-diquinomethane intermediates.

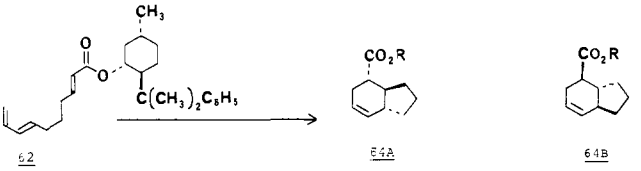
(30) (a) Morrison, J. D.; Mosher, H. S. "Asymmetric Organic Reactions"; Prentice-Hall: Englewood Cliffs, NJ, 1971, pp 252–257. (b) Walborsky, H. M.; Barash, L.; Davis, T. C. *Tetrahedron* **1963**, *19*, 2333. (c) Ensley, H. E.; Parnell, C. A.; Corey, E. J. *J. Org. Chem.* **1978**, *43*, 1610. (d) Trost, B. M.; O'Krongly, D.; Belletire, J. L. *J. Am. Chem. Soc.* **1980**, *102*, 7595. (e) Oppolzer, W.; Kurth, M.; Reichlin, D.; Moffatt, F. *Tetrahedron Lett.* **1981**, *22*, 2545.

Table VI



61 63A 63B

entry	catalyst, conditions, yield[a]	ratio[b] 63A	63B	de[c]
1	$TiCl_4$ (1.1 equiv), 23 °C, 6 h, 8%	86	14	72%
2	$TiCl_4$ (0.9 equiv)-$EtAlCl_2$ (0.2 equiv), 23 °C, 36 h, 25%	63	37	26%
3	$EtAlCl_2$ (0.9 equiv), 23 °C, 18 h, 21%[d]	58	42	16%
4[e]	(menthyloxy)$AlCl_2$ (1.8 equiv), 23 °C, 84 h, 75%	67	33	34%
5[e]	(menthyloxy)$AlCl_2$ (1.9 equiv), 8 °C, 10 days, 75%	68	32	36%
6	(*l*-menthyloxy)$AlCl_2$ (1.6 equiv), 23 °C, 92 h, 75%	65	35	30%
7	(*l*-bornyloxy)$AlCl_2$ (1.8 equiv), 23 °C, 92 h, 61%	67	33	34%
8	$AlCl_3$ (0.2 equiv), 50 °C, 12 h, 50%	40	60	−20%[f]



62 64A 64B

entry		ratio 64A	64B	de
9[e]	(menthyloxy)$AlCl_2$ (1.8 equiv), 23 °C, 6 days, 40%	75	25	50%
10	(*l*-bornyloxy)$AlCl_2$ (1.5 equiv), 23 °C, 36 h, 77–82%	82	18	64%
11	(*l*-bornyloxy)$AlCl_2$ (1.6 equiv), 8 °C, 14 days, 72%	86	14	72%

[a] Yield of isolated (chromatographed) product. [b] Ratio of diastereomers **63A** to **63B** was determined by gas chromatography (10-ft SE-30 column, 250 °C); ratio of **64A** to **64B** was determined by comparison of the optical rotation of **38** prepared by $LiAlH_4$ reduction of these mixmixtures to the maximum rotation ($[\alpha]_D^{25}$ 45.0° (*c* = 0.023, EtOH)) of optically pure **38**. [c] Diastereomer excess (de) corresponds to enantiomer excess. [d] 43% of **61** was recovered. [e] Racemic (menthyloxy)$AlCl_2$. [f] The major diastereomer from this cyclization corresponds to the minor product of the other runs.

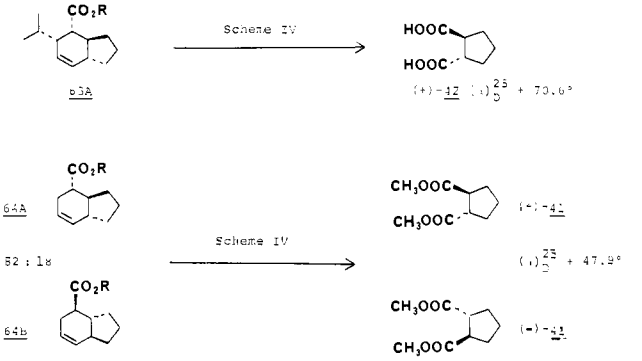
in refluxing benzene followed by deprotonation with NaOH afforded phosphorane **60**. This reagent smoothly condensed with aldehydes **32** (Scheme III) and **29** (Scheme II) to afford **61** and **62**, respectively, in 59–60% yield basd on bromoacetate **59**.

The results of the Lewis acid catalyzed cyclizations of **61** and **62** are summarized in Table VI. Each substrate afforded a mixture of two trans-fused, endo diastereomers. The ratio of these products corresponds to the enantiomeric excess of the cyclization, a measure of the efficiency of the chiral ester to direct cyclization to one or the other enantioface of the butadiene.

The rate of cyclization, yield, and ratio of diastereomers from these cyclizations varies with the Lewis acid employed. The carbonyl groups of **61** and **62** are much more hindered than the carbonyl groups of the corresponding methyl esters (**7** and **5**, respectively), and, as a consequence, diene polymerization is a more serious problem in these cases. Thus, reagents such as $EtAlCl_2$ and $AlCl_3$, which are among the more efficient catalysts for the cyclization of **7**, afforded relatively poor yields of cycloadduct from **61**. The best diastereomer excess with **61** was obtained by using $TiCl_4$ (entry 1, diastereomer excess = 72%). Unfortunately, the yield of product in this case was only 8% (olefin polymerization is a serious problem here). The yield of this cyclization was improved somewhat (25%) by doping the mixture with 0.2 equiv of $EtAlCl_2$, but under these conditions the diastereomer excess was only 26%. With $EtAlCl_2$ alone, the diastereomer excess was 16%. By far, the best reagents in terms of product yield and diastereomer excess are the alkoxyaluminum dihalides. Interestingly, racemic (menthyloxy)aluminum dichloride gives a slightly greater diastereomer excess (34%; entry 4) than does the chiral reagent prepared from *l*-menthol (30%; entry 6). Reaction temperature had a negligible effect on diastereomer excess (entries 4, 5).

The optical induction realized with **62** was higher than with **61**. (*l*-Bornyloxy)aluminum dichloride[24b] proved to be the best catalyst in this case, both in terms of reaction rate, yield, and optical induction. In contrast to the results with **61**, reaction temperature had a modest effect on diastereomer excess (entries 10, 11).

The absolute configuration of diastereomer **63A**, mp 125–127

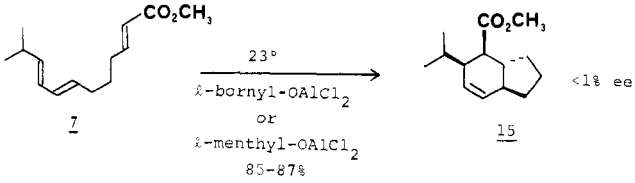


°C, which is easily purified by fractional crystallization of the mixture of products obtained from **61**, was determined by degradation to (+)-**42** (the absolute configuration of which is formulated in the accompanying diagram)[31] using the route outlined in Scheme IV. Similarly, an 82:18 mixture of **64A** and **64B** was degraded to a mixture of (+)- and (−)-**41** in which the (+) isomer predominated. Therefore, **64A** is the major product of the cyclization of **62**. It was expected that **63A** and **64A** would be the major products of cyclization of **61** and **62**, respectively, on the basis of the data previously reported by Walborsky[30b] and Corey.[30c]

(31) (a) Stork, G.; Schoofs, A. R. *J. Am. Chem. Soc.* **1979**, *101*, 5081. (b) Benedetti, E.; Corradini, P.; Pedone, C. *J. Phys. Chem.* **1972**, *76*, 790. (c) The (1*R*,2*R*)-(−)-isomer of **47** has been correlated with the (1*S*,2*S*)-(−)-isomer of 1,2-cyclopentanediacetic acid: Inouye, Y.; Sawada, S.; Ohno, M.; Walborsky, H. M. *Tetrahedron* **1967**, *23*, 3237. Bourn, P. M.; Klyne, W. *J. Chem. Soc.* **1960**, 2044.

It is surprising, therefore, that the $AlCl_3$-catalyzed cyclization of **61** (Table VI, entry 8) followed the opposite stereochemical course, affording diastereomer **63B** as the major product.

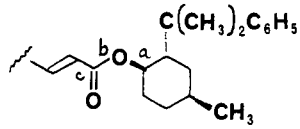
It was of interest to determine whether the asymmetry of the optically active Lewis acids (*l*-bornyloxy)aluminum dichloride and (*l*-menthyloxy)aluminum dichloride had an effect on the asymmetric induction in these cyclizations.[24] Accordingly, triene **7** was



7 15

cyclized in the presence of these chiral Lewis acids. In both cases, cycloadduct **15** was shown to be less than 1% optically pure by $LiAlH_4$ reduction to optically active **43** (Scheme IV). We infer from this result that the chirality of the optically active Lewis acids has a negligible effect on the results reported in Table VI.[32]

This preliminary study of asymmetric intramolecular Diels–Alder reactions has demonstrated that modest (30–64%) asymmetric induction can be achieved by using chiral dienophile esters. The induction realized in the cases of **64** and **65**, however, is not as great as has been obtained in bimolecular Diels–Alder reactions. We attribute these results in part to the temperatures required for cyclization. The greatest induction in bimolecular Diels–Alder reactions is generally realized when the reactions are performed at temperatures below 0 °C. The higher temperatures required for the cyclization of **61** and **62** exasperates the conformational



61

problems associated with asymmetric synthesis using chiral esters, as many reactive conformations resulting from rotations about bonds a, b, and c of the chiral dienophile are possible. It is also probable that steric interactions between the isopropyl and phenylmenthyl groups of **61** have a detrimental effect on the diastereomeric excess in this case.

Experimental Section

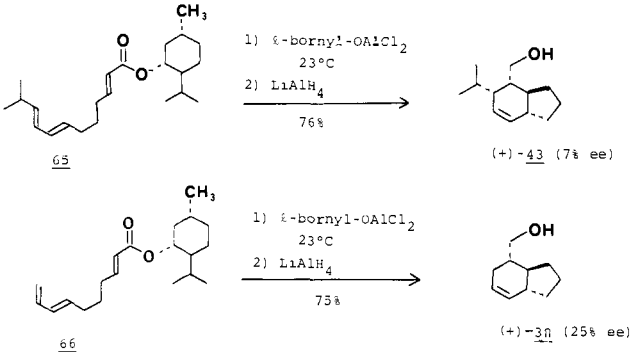
^1H NMR spectra were measured at 60 MHz on Perkin-Elmer R-24B and Varian T-60 instruments, at 100 MHz on a Varian XL-100 instrument (Harvard University), and at 250 MHz on a Bruker 250 instrument. Chemical shifts are reported in δ units relative to internal Me_4Si. ^{13}C NMR spectra were measured at 62.8 MHz on a Bruker 250 instrument; carbon resonances are reported in δ_C units calibrated against the 77.0-ppm line of $CDCl_3$. Infrared spectra were measured on a Perkin-Elmer Model 238B infrared spectrophotometer and were calibrated with the 1601-cm^{-1} absorption of polystyrene. Ultraviolet (UV) spectra were measured on a Carey Model 14 spectrophotometer. Mass spectra were measured at 70 eV on a Varian MAT 44 instrument (MIT) and an AEI MS-9 double-focusing instrument (Harvard University). High-resolution mass spectra were provided by the Facility supported by NIH Grant RR0317 (principal investigator, Professor K. Biemann) from the Biotechnology Resources Branch, Division of Research Resources, and were obtained on a CEC 21-110B high-resolution mass spectrometer equipped with an IBM 1800 computer system to process data recorded on photographic plates. Elemental analyses were performed by Robertson Laboratories, Florham Park, NJ. Silicon analyses were performed by Galbraith Laboratories, Knoxville, TN. Melting points were recorded on a Fisher-Johns hot-stage melting point apparatus and are uncorrected. Optical rotations were measured on a Perkin-Elmer 144 polarimeter using a 1-cm^3 capacity quartz cell (10-cm path length).

All reactions were conducted in oven-dried (120 °C) or flame-dried glassware under atmospheres of dry argon or nitrogen. All solvents were purified before use: ether, THF, and DME were distilled from sodium benzophenone ketyl; CH_2Cl_2 and Me_2SO were distilled from CaH_2; benzene was distilled from $LiAlH_4$; toluene was distilled from sodium metal. Preparative thin-layer chromatography (TLC) was performed by using 20 × 20 cm plates coated with 0.5- and 2-mm thicknesses of silica gel containing PF 254 indicator (Analtech). Unless indicated otherwise, compounds were eluted from the adsorbents with ether. Column chromatography was peformed by using activity I Woelm silica gel. All chromatography solvents were distilled prior to use.

2-((*E*)-3-Hydroxyhepta-4,6-dienyl)-1,3-dioxolane (21). Pentadienal[33] (**19**, 11.7 g, 0.143 mol), as a solution in 50 mL of dry THF, was added dropwise to a 0 °C solution of Grignard reagent **20** which was prepared from 36 g (0.20 mol) of 2-(2-bromoethyl)-1,3-dioxolane[34] and 6.5 g of Mg turnings (0.27 mol) in 200 mL of dry THF. The reaction was warmed to room temperature and stirred for 2 h prior to workup. The reaction was quenched with 10 mL of MeOH, and then the entire mixture was poured through a plug of glass wool into a separatory funnel containing 200 mL of saturated NH_4Cl solution. The resulting mixture was extracted with three 200-mL portions of ether. The combined extracts were dried (Na_2SO_4), filtered, and concentrated in vacuo to afford the crude product. Analysis of the crude product by TLC (4:1 hexane–EtOAc) indicated that the mixture contained two major products: R_f 0.47 and R_f 0.26. The slower band corresponded to **21**, and the faster moving band corresponded to the bis(ethylene acetal) of hexane-1,5-dial. The products were separated by column chromatography (300 g of silica gel, 4:1 hexane–EtOAc as eluent) to afford 1.62 g of the diacetal (8% based upon starting bromide) and 17.3 g (66%) of **21**. The yield of **21** was 81% from a similar run starting with 55 mmol of bromide and 33 mmol of pentadienal: NMR ($CDCl_3$, 100 MHz) δ 6.30 (m, 3 H), 5.72 (m, 1 H), 5.20 (m, 2 H), 4.92 (t,, J = 4 Hz, 1 H), 4.21 (br q, J = 6 Hz, 1 H), 3.93 (m, 4 H, OCH_2CH_2O), 2.30 (br s, 1 H, OH), 1.78 (m, 4 H); IR (neat) 3400, 1600 cm^{-1}; mass spectrum, *m/e* 184 (parent ion); UV (95% EtOH) λ_{max} (log ϵ) 223.5 (4.46). Anal. Calcd for $C_{10}H_{16}O_3$: C, 65.19; H, 8.75. Found: C, 65.12; H, 8.91.

2-Hydroxy-5-((*E*)-buta-1,3-dienyl)tetrahydrofuran (22). A solution of 10.2 g of **21** (55.4 mmol) in 75 mL of THF and 30 mL of H_2O was thoroughly degassed with argon, and then 15 mL of 1 N HCl (degassed) was added. This mixture was stirred for 48 h at 23 °C. It was then neutralized with aqueous Na_2CO_3 and was extracted with three 50-mL portions of CH_2Cl_2. The combined extracts were passed through a cotton plug and were evaporated in vacuo to give 8.3 g of crude product. Analysis of the crude product by analytical TLC (silica gel, 1:1 ether–hexane) indicated that it contained two major bands (R_f 0.47, corresponding to **22**, and R_f 0.18, corresponding to **23**) along with five

(32) We have also examined the Diels–Alder reactions of **65** and **66**, which were prepared by methods analogous to those outlined in Scheme V. The cyclizations of these trienes proved to be much less selective than **61** and **62**, a result in accord with previous studies of Diels–Alder reactions of menthyl vs. phenymenthyl esters.[30c,e]



65 (+)-43 (7% ee)

66 (+)-30 (25% ee)

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minor, less-polar spots. A portion of the crude product (200 mg) was chromatographed over silica gel to afford 137 mg of **22** (0.98 mmol) and 49 mg of **23** (0.27 mmol). Reaction conditions were not found which would provide a more favorable ratio of **22**:**23**. The products could be separated by chromatographic methods, and **23** could be recycled. However, as a consequence of the ready decomposition of **22** it was more convenient to use this mixture in the next step without purification.

Data for **22**: NMR ($CDCl_3$, 100 MHz) δ 6.1–6.6 (m, 3 H), 5.5–5.9 (m, 2 H), 5.1–5.4 (m, 2 H), 4.70 and 4.50 (two q, J = 7 Hz, 1 H, diastereomers), 1.5–2.3 (m, 4 H); IR (neat) 3350, 1600 cm^{-1}; mass spectrum, m/e 140 (parent ion); UV (95% EtOH) λ_{max} (log ϵ) 223.5 (4.45). Anal. Calcd for $C_8H_{12}O_2$: C, 68.54; H, 8.63. Found: C, 68.72; H, 8.76.

Methyl (*Z*,*E*)-6-Hydroxydeca-2,7,9-trienoate (4). A solution of 8.1 g of crude hemiacetal, **22**, containing approximately 20% of **23**, in 100 mL of anhydrous MeOH was treated with 18 g (55 mmol) of ((carbomethoxy)methylene)triphenylphosphorane.[10] The solution was stirred overnight at room temperature. Analysis of the crude product by TLC (silica gel, 1:1 ether–hexane) indicated that the mixture contained four major products (R_f 0.65 (**25**); R_f 0.44 (**4**); R_f 0.35 (**24**); R_f 0.18 (**23**)) as well as four minor, less-polar, components and triphenylphosphine oxide (R_f 0.05). MeOH was removed in vacuo, and the crystalline residue was roughly chromatographed (300 g of silica gel, 3–4:1 hexane–EtOAc) to afford 2.9 g (27%) of **25** (NMR δ 3.62 (s, 3 H); IR (neat) 1735, 1650 (w), 1600 (m) cm^{-1}; mass spectrum, m/e 196 (parent ion)), 6.1 g of a mixture of **25**, **4**, and **24**, and 1.8 g (18%) of **23** (NMR δ 3.63 (s, 4 H, OCH_2CH_2OH); IR (neat) 3400, 1650 (w), 1600 (m) cm^{-1}; mass spectrum, m/e 184 (parent ion)). The mixture of three components was further separated by preparative HPLC (Waters 500 LC, two 1-m columns in series, 4:1 hexane–EtOAc) to give 1.0 g of **25** (9%; 36% total), 1.46 g (13%) of **4**, and 2.45 g (22%) of **24**.

Data for **4**: NMR ($CDCl_3$, 100 MHz) δ 6.1–6.6 (m, 4 H), 5.82 (dt, $J_{2,3}$ = 11 Hz, $J_{2,4}$ = 1 Hz, H_2), 5.75 (m, 1 H), 5.0–5.4 (m, 2 H), 4.8 (br q, J = 6 Hz, 1 H), 3.71 (s, 3 H), 2.62 (m, 2 H, H_4), 1.70 (m, 2 H); IR (neat) 3350, 1720, 1630 (s), 1600 (w) cm^{-1}; mass spectrum, m/e 196 (parent ion); UV (95% EtOH) λ_{max} (log ϵ) 222.5 (4.44). Anal. Calcd for $C_{11}H_{16}O_3$: 67.32; H, 8.22. Found: C, 66.49; H, 8.34. It was subsequently observed that **4** polymerizes readily. High-resolution mass spectrum: calculated, 196.109 94; found, 196.112 07.

Data for **24**: NMR ($CDCl_3$, 100 MHz) δ 6.99 (dt, J = 15, 7 Hz, H_3), 6.1–6.5 (m, 3 H), 5.85 (dt, J = 15, 1 Hz, H_2), 5.7 (m, 1 H), 5.1–5.3 (m, 2 H), 4.17 (br q, J = 6 Hz, H_6), 3.72 (s, 3 H), 2.31 (m, 2 H, H_4), 1.70 (m, 2 H, H_5); IR (neat) 3400, 1720, 1650 (s), 1600 (w) cm^{-1}, mass spectrum, m/e 196 (parent ion). Anal. Calcd for $C_{11}H_{16}O_3$: C, 67.32; H, 8.22. Found: C, 66.81; H, 8.22. It was subsequently found that **24** polymerizes readily.

Hydrolysis of Acetal 23. A solution of 105 mg of **23** (0.57 mmol) in 1.5 mL of THF and 0.5 mL of 1 N HCl was thoroughly degassed with argon and stirred for 24 h at 23 °C. The reaction was then quenched with excess saturated Na_2CO_3 and was extracted with three 10-mL portions of CH_2Cl_2. Separation of the products by preparative TLC as described above afforded 41 mg (52%) of **22** plus 18 mg (17%) of recovered **23**.

Ethyl Hepta-4(*E*),6-dienoate (26).[35] A solution of 30.4 g (0.362 mol) of divinyl carbinol,[36] 460 mL (2.51 mol) of triethyl orthoacetate, and 0.24 g (3.3 mmol) of propionic acid was refluxed for 3 h under conditions for distillative removal of ethanol.[37] A few crystals of BHT were added, and the resulting solution was carefully fractionally distilled to give **26**: 36.2 g (71%); bp 96 °C (24 mm); NMR ($CDCl_3$, 250 MHz), δ 6.30 (dt, J = 16.8, 10.1 Hz, 1 H), 6.09 (dd, J = 16.8, 10.3 Hz, 1 H), 5.69 (m, 1 H), 5.12 (dd, J = 17.1, 1.5 Hz, 1 H), 5.00 (dd, J = 10.1, 1.5 Hz, 1 H), 4.13 (q, J = 7.0 Hz, 2 H), 2.41 (m, 4 H), 1.26 (t, J = 7.0 Hz, 3 H). This material contained less than 10% of the (*Z*)-butadiene isomer (250-MHz NMR analysis).

Hepta-4(*E*),6-dienol (27). To a stirred suspension of 2.63 g (69 mmol) of $LiAlH_4$ in 90 mL of dry ether at 0 °C was added 9.96 g (69 mmol) of **26** in 60 mL of dry ether. The reaction mixture was warmed to room temperature and after 1 h was quenched by sequential addition of EtOAc, MeOH, and H_2O (with external cooling). The solution was diluted with 300 mL of ice cold 1 N HCl and was extracted three times with ether. The combined extracts were washed with saturated $NaHCO_3$ and dried (Na_2SO_4). The solution was filtered and distilled to give pure **27**: 6.12 g (79%); bp 96–97 °C (27 mm); NMR (CCl_4, 60 MHz) δ 4.7–6.8 (m, 5 H), 3.5 (t, J = 7 Hz, 2 H), 2.15 (q, J = 7 Hz, 2 H), 1.70 (m, 2 H); IR (neat) 3330, 1650, 1605 cm^{-1}; mass spectrum, m/e 112 (parent ion). Anal. Calcd for $C_7H_{12}O$: C, 74.94; H, 10.80. Found: C, 74.70; H, 10.69.

Octa-5(*E*),7-dienenitrile (28). Methanesulfonyl chloride (8.17 mL, 105 mmol) was added dropwise to a 0 °C solution of 8.71 g (78 mmol) of **27** and 15.7 g (156 mmol) of Et_3N in 250 mL of dry CH_2Cl_2. The reaction mixture was stirred at 0 °C for 2 h and then was poured into a separatory funnel containing ice cold 1 N HCl. The aqueous layer was separated and was extracted with three portions of CH_2Cl_2. The combined extracts were washed with saturated $NaHCO_3$, dried (Na_2SO_4), filtered, and evaporated to give the crude mesylate. This material was then combined with 9.4 g (144 mmol) of KCN and 80 mL of 80:20 EtOH–H_2O, and this mixture was refluxed for 18 h. The cooled solution was diluted with brine and was extracted with ether (3×). The combined extracts were dried (Na_2SO_4), filtered, and distilled to give pure **28**: 7.23 g (77%); bp 115 °C (24 mm); NMR (CCl_4, 60 MHz) δ 4.8–6.7 (m, 5 H), 2.3 (m, 4 H), 1.8 (m, 2 H); IR (neat) 2260, 1650, 1605 cm^{-1}; mass spectrum, m/e 121 (parent ion). Anal. Calcd for $C_8H_{11}N$: C, 79.28; H, 9.17. Found: C, 79.36; H, 9.18.

Methyl (*E*,*E*)-Deca-2,7,9-trienoate (5) and Methyl (*Z*,*E*)-Deca-2,7,9-trienoate (6). To a solution of 1.61 g (13.3 mmol) of **28** in 26 mL of dry ether at 0 °C was added dropwise 19.8 mL of 1 M DIBAL in hexane (19.8 mmol).[38] The solution was warmed to room temperature and was stirred for 4.5 h. The solution was cooled to 0 °C, and then 10 mL of methanol was added followed by 50 mL of 1 N HCl. This two-phase mixture was stirred for 2 h at room temperature and then was extracted with ether (3×). The organic extracts were washed with saturated $NaHCO_3$, dried (Na_2SO_4), filtered, and concentrated to give crude **29**.

Crude **29**, without purification, was treated with 4.88 g (14.6 mmol) of ((carbomethoxy)methylene)triphenylphosphorane in 14 mL of CH_3OH.[10] The solution was stirred for 18 h at 23 °C, and then solvent was removed in vacuo. The residue was chromatographed over 100 g of silica gel using 10% ether–hexane as eluant (25-mL fractions). Fractions 4–9 afforded 0.43 g (18%) of **6** and fractions 11–17 afforded 0.97 g of **5** (41%). The 250-MHz ^1H NMR spectra of **5** and **6** revealed the presence of <7% of the *cis*-butadiene isomers.

Data for **5**: NMR ($CDCl_3$, 250 MHz) δ 6.95 (dt, J = 15.9, 7.0 Hz, H_3), 6.26 (dt, J = 16.8, 10.4 Hz, H_9), 6.04 (dd,, J = 15, 10.4 Hz, H_8), 5.82 (dt, J = 15.9, 1.6 Hz, H_2), 5.66 (dt, J = 15, 7.5 Hz, H_7), 5.08 (dd, J = 16.8, 0.6 Hz, $H_{10\text{-}syn}$, 4.97 (dd, J = 10.4, 0.6 Hz, $H_{10\text{-}anti}$), 3.72 (s, 3 H), 2.20 (dq, J = 1.6, 7.9 Hz, 2 H, H_4), 2.10 (br q, J = 7.5 Hz, 2 H, H_6), 1.52 (q, J = 7.3 Hz, 2 H, H_5); IR (neat) 1720, 1655, 1602 cm^{-1}; mass spectrum, m/e 180 (parent ion). Triene **5** was further characterized by conversion to the known maleic anhydride Diels–Alder adduct (1.5 equiv of maleic anhydride, toluene, 80 °C, 8 h, 84%), mp 96.5–97.5 °C (lit.[31] mp 96–97 °C).

Data for **6**: NMR ($CDCl_3$, 250 MHz) δ 6.24 (dt, J = 16.8, 10.4 Hz, H_9), 6.15 (dt, J = 11.5, 7.6 Hz, H_3), 5.99 (br dd, J =

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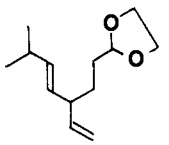
10.4, 15.3 Hz, H_8), 5.72 (dt, J = 11.5, 1.5 Hz, H_2), 5.63 (dt, J = 15.3, 7.3 Hz, H_7), 5.02 (br d, J = 16.8 Hz, $H_{10\text{-syn}}$), 4.89 (br d, J = 10.4 Hz, $H_{10\text{-anti}}$), 3.63 (s, 3 H), 2.60 (dq, J = 1.5, 7.6 Hz, 2 H, H_4), 2.06 (q, J = 7.3 Hz, 2 H, H_6), 1.48 (q, J = 7.5 Hz, 2 H, H_5); IR (neat) 1725, 1645, 1605 cm^{-1};f mass spectrum, m/e 180 (parent ion). Triene **6** was further characterized as the maleic anhydride Diels–Alder adduct (prepared by heating **6** and 1.1 equiv of maleic anhydride in 2 mL of toluene at 80 °C for 5 h): mp 48.5–49.0 °C; NMR ($CDCl_3$, 90 MHz) δ 6.24 (dt, J = 11.2, 7.3 Hz, 1 H), 5.84 (m, 3 H), 3.69 (s, 3 H), 3.37 (m, 2 H), 2.67 (m, 3 H), 2.28 (m, 2 H), 1.65 (m, 4 H); IR (CCl_4) 1855, 1785, 1725, 1645 cm^{-1}; mass spectrum (no parent ion). Anal. Calcd for $C_{15}H_{18}O_5$: C, 64.73; H, 6.53. Found: C, 64.67; H, 6.50.

The Wittig reaction of **29** in CH_2Cl_2 afforded 47–60% of **5** and 4–5% of **6** starting from **28**.

(*E*,*E*)-9-Methyldeca-5,7-dienal Ethylene Acetal (31). A mixture of 5.66 g (45.0 mmol) of **30**,[4] 7.28 mL of pyridine (90.0 mmol), and 6.93 mL of acetic anhydride (73.5 mmol) was stirred overnight at 23 °C. The mixture was diluted with 15 mL of 1 N HCl and was extracted with three 15-mL portions of ether. The combined extracts were washed with saturated $NaHCO_3$, dried (Na_2SO_4), filtered, and concentrated in vacuo to give 7.87 g of crude acetate. Purification of this material by distillation afforded pure acetate: 6.06 g (80%); bp 72 °C (2.3 mm); NMR (CCl_4, 60 MHz) δ 5.25–6.40 (m, 4 H), 4.45 (d, J = 7 Hz, CH_2OAc), 2.28 (m, 1 H), 1.98 (s, 3 H), 1.05 (d, J = 7 Hz, 6 H).

A solution of 6.02 g (36.9 mmol) of the above acetate was dissolved in 40 mL of dry THF, and 15 mL of a 0.11 M solution of Li_2CuCl_4 in THF (1.65 mmol) was added.[39] This solution was cooled to −10 °C and then the Grignard reagent **20**[34] prepared from 10.1 g (55.9 mmol) of 2-(2-bromoethyl)-1,3-dioxolane and 3.0 g (120 mmol) of Mg in 90 mL of THF was added dropwise over 80 min. The reaction mixture was then stirred at 0 °C for 3 h and at room temperature overnight. The reaction was then diluted with ether and was extracted with two portions of saturated aqueous NH_4Cl (adjusted to pH 8 with NH_4OH). The aqueous extracts were back-extracted with ether (2×). The combined organic extracts were dried (Na_2SO_4), filtered, and concentrated in vacuo. The crude product, which contained some unconsumed acetate, was dissolved in 100 mL of 3:1 CH_3OH–H_2O containing 1 N NaOH and was stirred overnight at room temperature. The reaction was diluted with 200 mL of one-half saturated aqueous $NaHCO_3$ and was extracted with ether (2×). The combined extracts were dried (Na_2SO_4), filtered, and concentrated in vacuo to give 8.48 g of crude product. Analysis of the crude product by analytical TLC (silica gel, 10% Et_2O–hexane) revealed the presence of two closely separated products: **31**, R_f 0.45, and an S_N2'-coupling product (i), R_f 0.50. These compounds were



(i)

separated by careful chromatography over 300 g of silica gel using 5% ether–hexane as eluant; all mixed fractions were rechromatographed. In this manner there was obtained 5.03 g (65%) of **31** and 0.79 g (10%) of i. The NMR, IR, and mass spectra of i were fully consistent with the assigned structure.

Data for **31**: NMR ($CDCl_3$, 60 MHz) δ 5.20–6.10 (m, 4 H), 4.80 (t, J = 4 Hz, 1 H), 3.65–4.00 (m, 4 H), 1.85–2.6 (m, 3 H), 1.35–1.70 (m, 4 H), 1.00 (d, J = 7 Hz, 6 H); IR (neat) 2965, 2875, 1640, 1410, 1135, 983, 840 cm^{-1}; mass spectrum, m/e 210 (parent ion). Anal. Calcd for $C_{13}H_{22}O_2$: C, 74.24; H, 10.54. Found: C, 74.16; H, 10.43.

(*E*,*E*)-9-Methyldeca-5,7-dienal (32). A mixture of 1.19 g (5.65 mmol) of **31** in 16 mL of THF, 20 mL of H_2O, and 10 mL of acetic acid was refluxed for 2 h. The reaction was neutralized with 150 mL of saturated aqueous $NaHCO_3$, and the resulting two-phase mixture was extracted with four 75-mL portions of hexane. The combined extracts were dried (Na_2SO_4), filtered, and evaporated to give 1.06 g of crude **32**. This material was purified by chromatography on 40 g of silica gel (6:1 hexane–ether), giving pure **32**: 0.863 g (92%); NMR (CCl_4, 60 MHz) δ 9.70 (t, J = 1 Hz, 1 H), 5.10–6.20 (m, 4 H), 1.45–2.50 (m, 7 H), 1.00 (d, J = 7 Hz, 6 H); IR (neat) 2960, 2710, 1725, 1455, 1358, 980 cm^{-1}; mass spectrum, m/e 166 (parent ion). High-resolution mass spectrum: calculated for $C_{11}H_{18}O$, 166.13576; found, 166.13792.

Methyl (*E*,*E*,*E*)-11-Methyldodeca-2,7,9-trienoate (7) and Methyl (*Z*,*E*,*E*)-11-Methyldodeca-2,7,9-trienoate (8). A solution of 3.20 g of **32** (19.3 mmol, the crude product obtained by hydrolysis of 4.06 g of acetal **31**) in 40 mL of dry CH_2Cl_2 was treated with 7.41 g (22.2 mmol) of ((carbomethoxy)methylene)triphenylphosphorane.[10] The reaction was stirred overnight under argon at room temperature. The solvent was then removed in vacuo, and the crystalline residue was triturated with hexane (6×), giving 4.27 g of crude trienes. This material was chromatographed over 110 g of silica gel using 5% ether–hexane as eluant; 25-mL fractions were collected. Fractions 7–14 afforded 262 mg (6.1%) of **8** and fractions 15–26 afforded 3.38 g (79%) of **7**. When this Wittig reaction was performed in CH_3OH, **7** and **8** were obtained in 43–51% and 23–30% yields, respectively.

Data for **7**: NMR ($CDCl_3$, 250 MHz) δ 6.84 (dt, J = 15.4, 7.5 Hz, H_3), 5.97 (m, 2 H), 5.79 (dt, J = 15.4, 1.4 Hz, H_2), 5.51 (m, 2 H), 3.69 (s, 3 H), 2.25 (m, 1 H), 2.18 (dq, J = 1.4, 7.5 Hz, 2 H, H_4), 2.06 (q, J = 7.3 Hz, 2 H), 1.51 (m, 2 H), 0.96 (d, J = 6.9 Hz 6 H); IR (neat) 2965, 2875, 1733, 1662, 1460, 1438, 1325, 1272, 1200, 1090, 984, 848, 712 cm^{-1}; mass spectrum, m/e 222 (parent ion). Anal. Calcd for $C_{14}H_{22}O_2$: C, 75.63; H, 9.97. Found: C, 75.64; H, 9.86.

Data for **8**: NMR ($CDCl_3$, 250 MHz) δ 6.22 (dt, J = 11.6, 7.6 Hz, 1 H), 5.99 (m, 2 H), 5.78 (dt, J = 11.6, 1.8 Hz, 1 H), 5.57 (m, 2 H), 3.70 (s, 3 H), 2.67 (dq, J = 1.8, 7.6 Hz, 2 H), 2.31 (m, 1 H), 2.11 (q, J = 7.3 Hz, 2 H), 1.55 (m, 2 H), 0.99 (d, J = 6.8 Hz, 6 H); IR (neat) cm^{-1} 2980, 2875, 1730, 1645, 1438, 1412, 1298, 1263, 984, 810, 780, 758; mass spectrum, m/e 222 (parent ion). Anal. Calcd for $C_{14}H_{22}O_2$: C, 75.63; H, 9.97. Found: C, 75.86; H, 10.20.

Intramolecular Diels–Alder Reaction of 4: Methyl 1β-Hydroxy-2,3,3aβ,4,5,7aα-hexahydroindene-4α-carboxylate (9a), Methyl 1α-Hydroxy-2,3,3aβ,4,5,7aα-hexahydroindene-4α-carboxylate (9b), and Methyl 1β-Hydroxy-2,3,3aβ,4,5,7aβ-hexahydroindene-4α-carboxylate (10a). A solution of **1**.15 g of **4** (5.86 mmol) in 15 mL of dry toluene was treated with **1**.5 mL of bis(trimethylsilyl)acetamide (6.0 mmol) and 50 mg of hydroquinone. The resulting solution was transferred to a resealable Carius tube and was degassed with argon. The sealed tube was allowed to stand at 23 °C overnight and then was heated at 185 °C for 7 h. The contents of the tube were transferred to a round-bottomed flask, and the volatile components were removed in vacuo. GC analysis (10-ft 4.1% Zonyl E-7 column, 150 °C) of the crude product indicated that the Me_3Si ethers of **9a**, **10a**, and **9b** were present in the ratio of 42:32:26 (in order of increasing retention time). The remainder of the crude product was dissolved in 25 mL of MeOH and was treated with 5 mL of 1 N HCl for 2 h at 23 °C. This mixture was diluted with 100 mL of saturated $NaHCO_3$ and was extracted with three 25-mL portions of CH_2Cl_2. The combined extracts were passed through a cotton plug and were concentrated in vacuo to give the crude product. Analytical TLC (silica gel, 2% MeOH–CH_2Cl_2, two developments) indicated that this material was mainly a mixture of three components: **9a**, R_f 0.45; **10a**, R_f 0.37; and **9b**, R_f 0.30. A small portion of the crude product (~70 mg) was chromatographed (three 0.5-mm silica gel plates, 2% MeOH–CH_2Cl_2, three developments) to give 19 mg of **9a**, 9 mg of **9b**, and 14 mg of **10a** which contained ca. 20% of **9a** (NMR analysis). The combined yield of chromatographed products from a smaller scale experiment (175 mg) was 73%.

(39) (a) Samain, D.; Descoins, C.; Commeron, A. *Synthesis* **1978**, 388. (b) Fouquet, G.; Schlosser, M. *Angew. Chem., Int. Ed. Engl.* **1974**, *13*, 82. (c) Preparation of Li_2CuCl_4: Tamura, M.; Kochi, J. *Synthesis* **1971**, 303.

Data for **9a**: mp 39–43 °C (ether–hexane); NMR ($CDCl_3$) δ 5.92 (br d, J = 10 Hz, 1 H), 5.76 (m, 1 H), 4.32 (dd, J = 4, 5 Hz, H_1), 3.67 (s, 3 H), 3.06 (m, $W_{1/2}$ = 13 Hz, H_4); IR (CH_2Cl_2) 3550, 3400, 1725 cm^{-1}; mass spectrum, m/e 196 (parent ion). Anal. Calcd for $C_{11}H_{16}O_3$: C, 67.32; H, 8.22. Found: C, 67.14; H, 8.13.

Data for **9b**: NMR ($CDCl_3$) δ 6.01 (dq, J = 10, 2 Hz, 1 H), 5.64 (ddt, J = 10, 4, 2 Hz, 1 H), 3.81 (dt, J = 5, 8 Hz, H_1), 3.67 (s, 3 H), 2.92 (m, $W_{1/2}$ = 13 Hz, H_4); IR (CH_2Cl_2) 3550, 1720 cm^{-1}; mass spectrum, m/e 196 (parent ion). Anal. Calcd for $C_{11}H_{16}O_3$: C, 67.32; H, 8.22. Found: C, 67.07; H, 8.13.

Data for **10a**: NMR ($CDCl_3$) δ 5.71 (d of quint, J = 10, 2.5 Hz, 1 H), 5.46 (d of quint, J = 10, 1 Hz, 1 H), 4.07 (m, $W_{1/2}$ = 8 Hz, H_1), 3.69 (s, 3 H); IR (CH_2Cl_2) 3550, 3400, 1725 cm^{-1}; mass spectrum, m/e 196 (parent ion). Anal. Calcd for $C_{11}H_{16}O_3$: C, 67.32; H, 8.22. Found: C, 67.08; H, 8.17.

General Procedure for Thermal Cyclizations of 5–8. A solution of triene in dry toluene (less than 1 M) was transferred to a resealable Carius tube. The solution was degassed with a stream of argon. The tube was sealed and heated in an oil bath under the conditions listed in Table I. The tube was cooled, and all volatile components were removed in vacuo. The product mixtures were analyzed by the methods indicated in the footnotes to Table I. The reaction products were chromatographed to give mixtures of cycloadducts in the yields indicated in Table I. Mixtures of **11** and **12** (from **5**) were separated by the selective saponification procedure described by House,[3i] giving acids **36** and **37**. These acids were esterified with ethereal CH_2N_2 to give pure samples of **11** and **12**, the spectroscopic properties of which were fully consistent with the published values.[3l] Mixtures of **13** and **14** (from **6**) and **17** and **18** (from **8**) were separated by preparative GC (12 ft × $^1/_4$ in. 5% SE-30 on Chromosorb G column; 125 °C for the mixture from **6**; 200 °C for the mixture from **8**). Mixtures of **15** and **16** (from **7**) were inseparable by TLC or GC. Pure samples of **15** were prepared by Lewis acid catalyzed cyclizations of **7** and by independent synthesis from **46**, as described below. Pure samples of **16** were obtained by epimerization of **18** and by independent synthesis from **47**.

Methyl 2,3,3aβ,4,5,7aα-Hexahydroindene-4β-carboxylate (11): NMR ($CDCl_3$, 250 MHz) δ 5.76 (br d, J = 10.0 Hz, 1 H), 5.52 (dq, J = 10.0, 3.0 Hz, 1 H), 3.61 (s, 3 H), 2.53 (dt, J = 7.0, 10.2 Hz, H_4), 2.35 (m, 1 H); IR (neat) 1735, 1640 cm^{-1}; mass spectrum, m/e 180 (parent ion).

2,3,3aβ,4,5,7aα-Hexahydroindene-4β-carboxylic Acid (36): mp 96.5–97.5 °C (lit.[3i] mp 90–91 °C); NMR ($CDCl_3$, 250 MHz) δ 5.83 (br d, J = 10 Hz, 1 H), 5.60 (dq, J = 10, 3 Hz, 1 H), 2.55 (dt, J = 10.7, 6.2 Hz, H_4), 2.36 (m, 1 H); IR (CCl_4) 3300–2500 (br), 1750, 1705, 1635 cm^{-1}; mass spectrum, m/e 166 (parent ion).

Methyl 2,3,3aα,4,5,7aα-Hexahydroindene-4α-carboxylate (12): NMR ($CDCl_3$, 250 MHz) δ 5.99 (d of multiplets, J = 10 Hz, 1 H), 5.74 (d of multiplets, J = 10 Hz, 1 H), 3.69 (s, 3 H), 2.43 (m, 1 H), 2.33 (m, 1 H), 2.20 (m, 1 H); IR (CCl_4) 1735, 1650 cm^{-1}; mass spectrum, m/e 180 (parent ion).

2,3,3aα,4,5,7aα-Hexahydroindene-4α-carboxylic Acid (37): mp 61.0–61.5 °C (lit.[3l] mp 58.5–60 °C); NMR ($CDCl_3$, 250 MHz) δ 5.75 (d of multiplets, J = 10 Hz, 1 H), 5.71 (d of multiplets, J = 10 Hz, 1 H), 2.45 (m, 1 H), 2.36 (m, 1 H), 2.25 (m, 1 H); IR (CCl_4) 3300–2500 (br), 1750 (w), 1705, 1650 cm^{-1}; mass spectrum, m/e 166 (parent ion).

Methyl 2,3,3aβ,4,5,7aα-Hexahydroindene-4α-carboxylate (13): NMR ($CDCl_3$, 250 MHz) δ 5.86 (br d, J = 10 Hz, 1 H), 5.60 (d of multiplets, J = 10 Hz, 1 H), 3.67 (s, 3 H), 3.00 (dd, J = 3.6, 6.6 Hz, H_4), 2.47 (d of multiplets, J = 17.5 Hz, 1 H), 2.29 (d of multiplets, J = 17.5 Hz, 1 H); IR (neat) 1730, 1640 cm^{-1}; mass spectrum, m/e 180 (parent ion). High-resolution mass spectrum: calculated for $C_{11}H_{16}O_2$, 180.1150; found, 180.1139.

Methyl 2,3,3aα,4,5,7aα-Hexahydroindene-4β-carboxylate (14): NMR ($CDCl_3$, 250 MHz) δ 5.61 (m, 1 H), 5.42 (br d, J = 10 Hz, 1 H), 3.69 (s, 3 H), 2.82 (ddd, J = 3.8, 5.6, 11.6 Hz, H_4), 2.70 (m, 1 H), 2.50 (m, 1 H); IR (CCl_4) 1735, 1650 cm^{-1}; mass spectrum, m/e 180 (parent ion). High-resolution mass spectrum: calculated for $C_{11}H_{16}O_2$, 180.1150; found, 180.1165.

Methyl 5β-(2-Propyl)-2,3,3aβ,4,5,7aα-hexahydroindene-4β-carboxylate (15): ^1H NMR ($CDCl_3$, 250 MHz) δ 5.95 (d, J = 10.0 Hz, 1 H), 5.55 (ddd, J = 10.0, 4.4, 2.6 Hz, 1 H), 3.65 (s, 3 H), 2.70 (dd, J = 11.4, 7.7 Hz, H_4), 2.60 (m, 1 H), 1.98 (m, 1 H), 0.96 (d, J = 7 Hz, 3 H), 0.84 (d, J = 7 Hz, 3 H; ^{13}C NMR ($CDCl_3$, 62.8 MHz) δ_c 174.8, 131.3, 126.0, 50.9, 50.4, 44.8, 43.6, 41.8, 30.2, 28.8, 28.6, 23.0, 22.2, 18.8; IR (neat) 1740, 1640 cm^{-1}; mass spectrum, m/e 222 (parent ion). Anal. Calcd for $C_{14}H_{22}O_2$: C, 75.63; H, 9.97. Found: C, 75.81; H, 10.09.

Methyl 5β-(2-Propyl)-2,3,3aα,4,5,7aα-hexahydroindene-4α-carboxylate (16): ^1H NMR ($CDCl_3$, 250 MHz) δ 5.89 (dt, J = 10, 4 Hz, 1 H), 5.58 (br d, J = 10 Hz, 1 H), 3.71 (s, 3 H), 2.37 (m, 3 H), 2.11 (dd, J = 10.8, 11.3 Hz, H_4), 0.99 (d, J = 7 Hz, 3 H), 0.80 (d, J = 7 Hz, 3 H); ^{13}C NMR ($CDCl_3$, 62.8 MHz; data obtained on a mixture of **15** and **16**) δ_c 177.0, 130.8, 125.9, 51.3, 47.2, 44.3, 40.7, 40.5, 32.4, 30.3, 29.3, 24.2, 20.7, 16.4; IR (CH_2Cl_2) 1735, 1650 cm^{-1}; a parent ion was not observed in the low-resolution mass spectrum. High-resoltuion mass spectrum: calculated for $C_{14}H_{22}O_2$, 222.1620; found, 222.1598.

Methyl 5β-(2-Propyl)-2,3,3aβ,4,5,7aα-hexahydroindene-4α-carboxylate (17): ^1H NMR ($CDCl_3$, 250 MHz) δ 5.95 (dt, J = 10, 1.5 Hz, 1 H), 5.56 (dt, J = 10, 3 Hz, 1 H), 3.66 (s, 3 H), 2.81 (d, J = 4.9 Hz, H_4), 2.33 (m, 1 H), 0.95 (d, J = 7 Hz, 3 H), 0.92 (d, J = 7 Hz, 3 H); ^{13}C NMR ($CDCl_3$, 62.8 MHz; only 13 carbon resonances observed, one degenerate signal) δ_c 175.7, 131.3, 128.7, 51.1, 44.7, 43.4, 43.2, 39.0, 33.2, 28.9, 27.2, 22.3, 20.2; IR (neat) 1735, 1640 cm^{-1}; mass spectrum, m/e 222 (parent ion). Anal. Calcd for $C_{14}C_{22}O_2$: C, 75.63; H, 9.97. Found: C, 75.93; H, 9.95.

Methyl 5β-(2-Propyl)-2,3,3aα,4,5,7aα-hexahydroindene-5β-carboxylate (18): ^1H NMR ($CDCl_3$, 250 MHz) δ 5.81 (dt, J = 10, 2.5 Hz, 1 H), 5.70 (br d, J = 10 Hz, 1 H), 3.60 (s, 3 H), 2.93 (t, J = 4.9 Hz, H_4), 2.44 (m, 2 H), 0.99 (d, J = 7 Hz, 3 H), 0.92 (d, J = 7 Hz, 3 H); ^{13}C NMR ($CDCl_3$, 62.8 MHz) δ_c 174.7, 130.7, 126.7, 50.7, 45.5, 44.5, 40.2, 39.8, 31.8, 29.9, 29.5, 25.0, 21.4, 20.9; IR (neat) 1735, 1650 cm^{-1}; mass spectrum, m/e 222 (parent ion). High-resolution mass spectrum: calculated for $C_{14}H_{22}O_2$, 222.1620; found, 222.1590.

Methyl 2,3,3aβ,4,5,7aβ-Hexahydroinden-1-one-4α-carboxylate (34). A solution of 60 mg of **9a** (0.31 mmol) in 1.5 mL of dry CH_2Cl_2 was added dropwise to a −78 °C solution of the reagent prepared from 0.044 mL of dry Me_2SO (0.63 mmol) and 0.077 mL of TFAA (0.53 mmol) in 1.5 mL of dry CH_2Cl_2.[12] The reaction was stirred at −78 °C for 15 min, and then 0.1 mL of dry Et_3N was added. The reaction was warmed to room temperature and was diluted with 25 mL of saturated aqueous $NaHCO_3$. The resulting solution was extracted with three 15-mL portions of ether. The combined extracts were washed with three 5-mL portions of 1 N HCl and one 5-mL portion of saturated $NaHCO_3$ and then were dried over Na_2SO_4. The filtered extracts were concentrated to afford crude **33** (NMR δ 6.03 (dq, J = 10, 2 Hz, 1 H), 5.62 (dq, J = 10, 4 Hz, 1 H), 3.70 (s, 3 H)) which upon silica gel chromatography (0.5-mm silica gel plate, 2:1 hexane–ether R_f 0.45) smoothly isomerized to afford 52 mg (86%) of **34**: NMR ($CDCl_3$) δ 5.83 (ddt, J = 10, 2, 2 Hz, 1 H), 5.48 (dtd, J = 10, 2, 0.5 Hz, 1 H), 3.72 (s, 3 H); IR (CH_2Cl_2) 1730 cm^{-1}; mass spectrum, m/e 194 (parent ion). High-resolution mass spectrum: calculated for $C_{11}H_{14}O_3$, 194.0943; found, 194.0933.

Methyl 1α-Hydroxy-2,3,3aβ,4,5,7aβ-hexahydroindene-4α-carboxylate (10b). A solution of 50 mg of **34** (0.26 mmol) in 1.5 mL of absolute ethanol was treated with 15 mg of $NaBH_4$ (0.4 mmol). The reaction was stirred at 23 °C for 1 h and then was quenched with 1 mL of 1 N HCl. The mixture was then diluted with 10 mL of saturated $NaHCO_3$ and was extracted with three 10-mL portions of CH_2Cl_2. The combined extracts were passed through a cotton plug and were concentrated in vacuo to afford 42 mg of crystalline crude product. The reaction products were separated by PTLC (two 0.5-mm silica gel plates, 2% CH_3OH–CH_2Cl_2, two developments), giving 2.0 mg of **10a** (4%, R_f 0.28) and 30 mg of **10b** (60%, R_f 0.39): mp 59–60 °C; NMR ($CDCl_3$) δ 5.96 (d quint, J = 10, 2.5 Hz, 1 H), 5.75 (br d, J = 10 Hz, 1 H), 4.26 (br q, J = 6 Hz, H_1), 3.68 (s, 3 H); IR (CH_2Cl_2) 3500,

3400, 1720 cm^{-1}; mass spectrum, *m/e* 196 (parent ion). Anal. Calcd for $C_{11}H_{16}O_3$: C, 67.32; H, 8.22. Found: C, 67.28; H, 8.15.

1α-Hydroxy-2,3,3aβ,4,5,7aβ-hexahydroindene-4α-carboxylic Acid δ-Lactone (35). A solution of 20 mg (0.10 mmol) of **10b** in 5 mL of dry, degassed benzene containing one small crystal of *p*-toluenesulfonic acid was refluxed overnight. The reaction mixture was diluted with CH_2Cl_2 and was extracted with saturated $NaHCO_3$. The CH_2Cl_2 extracts were passed through a cotton plug and concentrated in vacuo, giving 23 mg of crude δ-lactone. This material was purified by PTLC (0.5-mm silica gel plate, 1:1 ether–hexane), giving 13.3 mg (79%) of pure **35**: NMR ($CDCl_3$, 250 MHz) δ 5.96 (d of multiplets, J = 10.0 Hz, 1 H), 5.87 (d of multiplets, J = 10.0 Hz, 1 H), 4.64 (br s, H_1), 2.75 (m, $W_{1/2}$ = 10 Hz, H_4); IR (CH_2Cl_2) 1725 cm^{-1}; mass spectrum, *m/e* 164 (parent ion). High-resolution mass spectrum: calculated for $C_{10}H_{12}O_2$, 164.0837; found, 164.0832.

General Procedure for Ester Epimerization Experiments. A dilute solution of cycloadduct (either **12**, **13**, **15**, or **18**) in CH_3OH was transferred to a resealable Carius tube and was thoroughly degassed with a stream of argon. An excess of $NaOCH_3$ in CH_3OH was added, and the tube was sealed. The tube was then heated in an oil bath (80 °C for **12** and **13**; 100–120 °C for **15** and **18**) for 6–24 h. The cooled reaction mixture was diluted with 1 N HCl and was extracted with CH_2Cl_2. The crude product was treated with ethereal CH_2N_2 to give the equilibrated mixture of esters epimers. Mixtures of **11** and **13** and **15** and **17** were inseparable by GC or TLC; these mixtures were analyzed by 250-MHz NMR spectroscopy. Mixtures of **12** and **14** were analyzed by GC and were separated by preparative GC (12 ft × $^1/_4$ in. 5% SE-30 on Chromosorb G, 125 °C). Epimerization of **18** afforded only **16** (75%), which was purified by PTLC.

4β-(Hydroxymethyl)-2,3,3aβ,4,5,7aα-hexahydroindene (38). To a suspension of 167 mg (4.40 mmol) of $LiAlH_4$ in 4.5 mL of dry ether at 0 °C was added a solution of 483 mg (2.68 mmol) of **11** in 4.5 mL of ether. The solution was stirred at room temperature for 30 min and then cooled again to 0 °C. The residual $LiAlH_4$ was destroyed by addition of 3 mL of CH_3OH. This solution was then diluted with 1 N HCl and was extracted with ether (3×). The combined extracts were washed with saturated $NaHCO_3$ and dried over Na_2SO_4. The extracts were filtered and concentrated in vacuo, giving 405 mg of crude product. The product was purified by filtration through 10 g of silica gel using 200 mL of 2:1 hexane–ether as eluant, giving 365 mg (90%) of pure **38** which crystallized on storage in a refrigerator: mp 34–36 °C; NMR ($CDCl_3$, 250 HHz) δ 5.83 (br d, J = 10 Hz, 1 H), 5.62 (d of m, J = 10 Hz, 1 H), 3.71 (m, 1 H), 3.54 (m, 1 H), 2.30 (m, 1 H), 1.83 (m, 6 H), 1.22 (m, 4 H); IR (CH_2Cl_2) 3614, 2959, 2875, 1642, 1452 cm^{-1}; mass spectrum, *m/e* 152 (parent ion). Anal. Calcd for $C_{10}H_{16}O$: C, 78.90; H, 10.59. Found: C, 79.03; H, 10.50.

4β-(((*o*-Nitrophenyl)selenyl)methyl)-2,3,3aβ,4,5,7aα-hexahydroindene (39). To a solution of 363 mg (1.60 mmol) of (*o*-nitrophenyl)selenocyanate and 323 mg (1.60 mmol) of Bu_3P in 6 mL of dry THF was added 154 mg (1.00 mmol) of alcohol **38** in 6 mL of THF.[40] The resulting mixture was stirred for 2 h at room temperature. THF was then removed in vacuo, and the residue was directly applied to two 1.5-mm silica gel plates. These were then developed twice with 5% ether–hexane, giving 212 mg (63%) of **39**, a brilliant yellow solid, mp 91–95 °C, from the band centered at R_f 0.65: NMR (CCl_4, 60 MHz) δ 8.27 (d, J = 8 Hz, 1 H), 7.42 (m, 3 H), 5.77 (br d, J = 11 Hz, 1 H), 5.48 (br d, J = 11 Hz, 1 H), 2.80 (m, 3 H), 1.85 (m, 6 H), 1.33 (m, 4 H); IR (CH_2Cl_2) 3018, 2958, 2870, 1636, 1589, 1567, 1512 cm^{-1}; mass spectrum, *m/e* 336 (parent ion). High-resolution mass spectrum, calculated for $C_{16}H_{19}NO_2{}^{76}Se$, 334.0529; found, 334.0545.

4-Methylene-2,3,3aβ,4,5,7aα-hexahydroindene (40). A solution of 102 mg (0.30 mmol) of selenide **39** in 2.5 mL of CH_2Cl_2 was treated with 0.34 mL (3.0 mmol) of 30% aqueous H_2O_2.[41] The reaction was stirred vigorously at room temperature for 30 min, or until **39** was completely consumed, and then was diluted with 10 mL of ether. The solution was extracted with 10% aqueous KOH. The aqueous phase extracted with three 5-mL portions of ether. The combined organic extracts were dried over Na_2SO_4. Solids were then removed by filtration, and solvents were *carefully* removed in vacuo (0 °C water bath (30 mm, or higher, pressure)) to a final volume of approximately 0.5 mL. The crude product was diluted with 2 mL of dry pentane, whereupon a reddish brown solid precipitated. The pentane solution was separated, and the precipitate was triturated with ten 2-mL portions of pentane. The pentane extracts were filtered through 2 g of silica gel, and most of the pentane was removed in vacuo (0 °C water bath (>30 mm pressure)), giving a solution of extremely volatile **40** in ~0.5 mL of pentane. This material was used in the next step without further purification (see procedure for preparation of **41**). In one case, **40** was isolated by preparative plate chromatography (silica gel, pentane, R_f 0.9, 22% yield). The low yield in this case was attributed to volatility: NMR (CCl_4, 60 MHz) δ 5.72 (br d, J = 10 Hz, 1 H), 5.40 (d of m, J = 10 Hz, 1 H), 4.60 (br s, 2 H), 2.80 (m, 2 H), 1.2–2.2 (m, 8 H).

4β-(Hydroxymethyl)-5β-(2-propyl)-2,3,3aβ,4,5,7aα-hexahydroindene (43). Ester **15** (1.0 g, 4.5 mmol) was reduced with $LiAlH_4$ (258 mg, 6.8 mmol) in a total volume of 16 mL of ether using the procedure described for preparation of **38**. The crude product (873 mg) was purified by chromatography over 15 g of silica gel using 250 mL of 2:1 hjexane–ether as eluant, giving 854 mg (98%) of pure **43**: NMR (250 MHz, $CDCl_3$) δ 5.98 (d, J = 10.0 Hz, 1 H), 5.63 (d of m, J = 10 Hz, 1 H), 3.75 (m, 2 H), 2.46 (m, 1 H), 2.05 (m, 1 H), 1.6–2.0 (m, 7 H), 1.25 (m, 3 H), 1.02 (d, J = 6.4 Hz, 3 H), 0.83 (d, J = 6.4 Hz, 3 H); IR (neat) 3340, 3020, 2960, 2890, 1638, 1466, 1374 cm^{-1}; mass spectrum, *m/e* 194 (parent ion). Anal. Calcd for $C_{13}H_{22}O$: C, 80.36; H, 11.41. Found: C, 80.08; H, 11.55.

4β-(((*o*-Nitrophenyl)selenyl)methyl)-5β-(2-propyl)-2,3,3aβ,4,5,7aα-hexahydroindene (44). A solution of 873 mg (4.5 mmol) of **43** in 18 mL of dry THF was added dropwise to a mixture of 1.59 g (7.0 mmol) of (*o*-nitrophenyl)selenocyanate and 1.41 g (7.0 mmol) of Bu_3P in 18 mL of THF.[40] The resulting solution was stirred at room temperature for 2 h, and then THF was removed in vacuo. The resulting yellow residue was extracted with three 30-mL portions or ether, which were combined and evaporated. The product so obtained was chromatographed on 100 g of silica gel using 10% of ether–hexane as eluant giving 1.60 g (94%) of **44** (R_f 0.70) from the appropriate fractions: NMR (60 MHz, CCl_4) δ 8.12 (d, J = 10 Hz, 1 H), 7.33 (m, 3 H), 5.90 (br d, J = 10 Hz, 1 H), 5.52 (br d of m, J = 10 Hz, 1 H), 2.95 (m, 2 H), 2.45 (m, 1 H), 1.80 (m, 12 H), 1.00 (d, J = 7 Hz, 3 H), 0.82 (d, J = 7 Hz, 3 H); IR (neat) 3010, 2950, 2862, 1584, 1560, 1504, 1447 cm^{-1}; mass spectrum, *m/e* 378 (parent ion). High-resolution mass spectrum: calculated for $C_{19}H_{25}NO_2{}^{76}Se$, 376.1070; found, 376.1079.

4-Methylene-5β-(2-propyl)-2,3,3aβ,5,7aα-hexahydroindene (45). A solution of 1.60 g (4.25 mmol) of selenide **44** in 40 mL of THF was treated with 4.82 mL (42.5 mmol) of 30% aqueous H_2O_2.[41] The reaction was then stirred at room temperture overnight. The solution was diluted with 50 mL of ether and 40 mL of saturated $NaHCO_3$ solution. The aqueous phase was extracted with three 20-mL portions of ether. The combined extracts were dried (Na_2SO_4), filtered, and concentrated in vacuo (23 °C water bath (>40 mm pressure)) to give 1.95 g of crude product. Diene **45** was purified by chromatography on 50 g of silica gel using 100% pentane as eluant. The fractions containing **45** (R_f 0.90) were combined and carefully evaporated (23 °C water bath (>40 mm pressure)), giving 510 mg (68%) of volatile **45**: NMR (60 MHz, CCl_4) δ 5.75 (br d, J = 10 Hz, 1 H), 5.45 (br d of m, J = 10 Hz, 1 H), 4.65 (s, 1 H), 4.55 (s, 1 H), 2.45 (m, 2 H), 1.85 (m, 8 H), 0.90 (d, J = 7 Hz, 3 H), 0.85 (d, J = 7 Hz, 3 H); IR (neat) 2952, 2865, 1640, 1455 cm^{-1}; mass spectrum, *m/e* 176 (parent ion). High-resolution mass spectrum: calculated for $C_{13}H_{20}$, 176.1565;

(40) Grieco, P. A.; Gilman, S.; Nishizawa, M. *J. Org. Chem.* **1976**, *41*, 1485.

(41) Sharpless, K. B.; Young, M. W. *J. Org. Chem.* **1975**, *40*, 947.

found, 176.1555.

Dimethyl *trans*-Cyclopentane-1,2-dicarboxylate (41). A solution of 39 mg (0.22 mmol) of diene **45** in 5 mL of CCl_4 was added to a solution of 1.0 g (5.0 mmol) of $NaIO_4$ in 10 mL of distilled H_2O. Freshly distilled CH_3CN (5 mL) was then added followed by 1 mg (0.004 mmol) of $RuCl_3 \cdot H_2O$.[42] The resulting two-phase mixture was then vigorously stirred for 15 h at room temperature under N_2. The phases were then separated, and the organic phase was diluted with 15 mL of ether. The resulting opaque black solution was extracted with three 10-mL portions of 10% aqueous NaOH. The combined aqueous extracts were washed with ether and then were acidified to pH 1–2 by using concentrated HCl. The resulting solution was saturated with NaCl and was extracted with EtOAc (6 × 15 mL). The combined extracts were dried (Na_2SO_4), filtered, and concentrated in vacuo. The residue was triturated with acetone (3×), and the combined extracts were filtered. This solution was treated with excess ethereal CH_2N_2. The excess CH_2N_2 was destroyed with HOAc. The resulting solution was diluted with 15 mL of ether and was washed with saturated $NaHCO_3$. The extracts were dried (Na_2SO_4), filtered, and concentrated to give the crude product. This material was chromatographed on two 0.25-mm silica gel plates using 1% EtOAc–CH_2Cl_2 as eluant. The non-UV active band at R_f 0.55 (visualized under a bright light) was isolated, giving 24 mg (59%) of diester **41**. An analogous procedure was used to prepared **41** from **40**, with the exception that **40** was used as a solution in ~0.5 mL of pentane (37% overall yield from selenide **39**): NMR (60 MHz, CCl_4) δ 3.70 (s, 6 H), 3.05 (m, 2 H), 1.90 (m, 6 H); IR (CH_2Cl_2) 2947, 1723, 1427, 1368 cm^{-1}; a parent ion was not observed in the low-resolution mass spectrum.

***trans*-Cyclopentane-1,2-dicarboxylic Acid (42).** A solution of 24 mg (0.13 mmol) of diester **41** in 2 mL of 4:1 CH_3OH–H_2O containing 2 N NaOH was stirred overnight at room temperature. Methanol was then removed in vacuo, and the residue was diluted with 3 mL of 5% aqueous NaOH and 3 mL of ether. The organic phase was extracted with 5% aqueous NaOH (2×). The aqueous extracts were acidified to pH 1–2 by using concentrated HCl. This solution was then saturated with NaCl and was extracted with EtOAc (6 × 5 mL). The EtOAc extracts were dried (Na_2SO_4), filtered, and concentrated in vacuo to give a mass of fine grained yellow crystals. This solid was triturated with benzene (1×) and CH_2Cl_2 (2×) to remove the yellow color, leaving behind 13 mg (65%) of **42**, a white crystalline solid: mp 156–159 °C (lit.[14] mp 160–161 °C); NMR (250 MHz, Me_2SO-d_6) δ 12.12 (br s, 2 H), 2.91 (m, 2 H), 1.82 (m, 2 H), 1.66 (m, 4 H); IR (KBr) 2980 (very broad), 2640 (br), 1690 (br), 1422, 1385, 1310, 928 cm^{-1}; mass spectrum, *m/e* (no parent ion observed) 140 (M − H_2O). Treatment of **42** with CH_2N_2 regenerated **41**.

Independent Synthesis of 15: Deoxygenation of 46. A solution of 76 mg (0.32 mmol) of **46**[4] in 2 mL of dry THF was treated with 3 mg of imidazole and 76 mg (1.64 mmol) of NaH (50% oil dispersion). This mixture was stirred at room temperature for 15 min, and then 0.30 mL (5.0 mmol) of CS_2 was added.[15] The resulting solution was refluxed for 1 h, and then 0.68 g (4.82 mmol) of CH_3I was added. The reaction was refluxed for an additional 30 min and then was cooled to room temperature. The reaction was quenched with 0.5 mL of HOAc and then was immediately diluted with saturated $NaHCO_3$. This solution was extracted with ether (3 × 5 mL). The combined extracts were dried (Na_2SO_4), filtered, and concentrated in vacuo. The crude product was purified by chromatography on silica gel (two 0.5-mm plates developed with 10% ether–hexane, R_f 0.40), giving 79 mg of the xanthate ester (74%): NMR (CCl_4, 60 MHz) δ 6.00 (m, 2 H), 5.61 (br d, J = 10 Hz, 1 H), 3.68 (s, 3 H), 2.60 (m, 3 H), 2.52 (s, 3 H), 2.10 (m, 6 H), 1.70 (m, 1 H), 1.00 (d, J = 7 Hz, 3 H), 0.82 (d, J = 7 Hz, 3 H); IR (neat) 3025, 2964, 1738, 1640, 1450, 1306, 1208, 1050, 782 cm^{-1}, mass spectrum, *m/e* 328 (parent ion).

The xanthate ester (75 mg, 0.23 mmol), without further purification, was dissolved in 5 mL of dry toluene. This solution was added dropwise over 1.5 h to a refluxing solution of 0.11 mL (0.35 mmol) of *n*-Bu_3SnH in 3 mL of toluene.[15] The solution was refluxed for an additional 6 h and then was cooled to room temperature. All volatile components of the mixture were removed in vacuo, and the residue was chromatographed (0.5-mm silica gel plate, 10% ether–hexane, R_f 0.5) to give 25 mg (49%) of **15**. Compound **15** prepared in this manner was in all respects identical with **15** prepared by the Diels–Alder reaction of **7**.

Deoxygenation of 47. Deoxygenation of **47**[4] was performed by using the methods described above for deoxygenation of **46**. Thus, **47** was transformed into the corresponding xanthate ester in 41% yield: NMR (60 MHz, CCl_4) δ 6.00 (d, J = 10 Hz, 1 H), 5.55 (m, 2 H), 3.63 (s, 3 H), 2.57 (m, 2 H), 2.53 (s, 3 H), 2.12 (m, 2 H), 1.90 (m, 2 H), 1.65 (m, 3 H), 0.91 (d, J = 7 Hz, 3 H), 0.71 (d, J = 7 Hz, 3 H); IR (neat) 3028, 2959, 2875, 1732, 1650, 1450, 1370, 1310 cm^{-1}; no parent ion was observed in the mass spectrum. This xanthate ester was reduced by *n*-Bu_3SnH in refluxing toluene to give **16** in 55% yield.

Lewis Acid Catalyzed Diels–Alder Reactions of 5–8. The two following procedures are representative.

1. Et_2AlCl-Catalyzed Cyclization of 7. A solution of 1.50 g (6.76 mmol) of triene **7** in 8 mL of dry CCl_4 was treated with 4.5 mL (6.1 mmol) of a 1.36 M solution of Et_2AlCl in hexane.[43] The resulting solution was stirred for 24 h at room temperature.[44] An additional 2.3 mL (3.2 mmol) of the Et_2AlCl solution was added, and the reaction was stirred for an additional 24 h. The reaction was then diluted with excess 1 N HCl and was extracted with ether (3×). The combined extracts were washed with saturated $NaHCO_3$ solution and then were dried (Na_2SO_4) and filtered. This solution was concentrated in vacuo, giving crude **15**. This compound was purified by chromatography over 80 g of silica gel using 5% ether–hexane as eluant. The appropriate fractions were combined and concentrated to give 1.27 g (85%) of pure **15** (R_f 0.60). There was also obtained 0.17 g (11%) of uncyclized triene (R_f 0.45), an approximate 1:1 mixture of **7** and its 9,10(*Z*)-olefin isomer. Approximately 7% of this double-bond isomer is present in **7** and in each of its precursors.[4]

2. (Menthyloxy)aluminum Dichloride Catalyzed Cyclization of 5. A stock solution of racemic (menthyloxy)aluminum dichloride was prepared by treating a solution of 1.37 g (8.78 mmol) of menthol in 15 mL of dry CH_2Cl_2 with 4.93 mL (8.78 mmol) of a 1.78 M solution of ethylaluminum dichloride in toluene at 0 °C.[24a] This solution was stirred at room temperature for 2 h prior to use. Such stock solutions can be stored up to 48 h at room temperature without apparent decomposition. The reagent crystallizes from solution at 6 °C.

Triene **5** (612 mg, 3.40 mmol), neat, was treated with 7.20 mL of the above stock solution (assumed to be 0.44 M in (menthyloxy)aluminum dichloride, 3.2 mmol). The resulting mixture was stirred for 36 h at room temperature under argon.[44] An additional 3.0 mL (1.3 mmol) of the reagent solution was then added, and the reaction was stirred for an additional 24 h. The reaction mixture was then diluted with excess 1 N HCl and was extracted with ether (3×). The extracts were washed with saturated $NaHCO_3$, dried (Na_2SO_4), and filtered. This solution was concentrated in vacuo, giving crude **11**. This compound was purified by chromatography over 90 g of silica gellusing 10% ether–hexane as eluant. The appropriate fractions (R_f 0.65) were pooled and concentrated, giving 483 g (79%) of pure **11**.

(42) Oxidation of **45** to **42** was originally performed using catalytic RuO_2 and $NaIO_4$ in acetone–H_2O. This procedure gave variable and nonreproducible results (yield of **42** ranged from 0 to 53%). Oxidation of **45** with catalytic RuO_4 and $NaIO_4$ in acetone–H_2O followed by CH_2N_2 esterification afforded only a trace of **41** (TLC analysis). We thank Professor K. B. Sharpless for suggesting the use of $RuCl_3$–$NaIO_4$ in the CCl_4–CH_3CN–H_2O solvent system. For other applications of this reagent, see: Rossiter, B. E.; Katsuki, T.; Sharpless, K. B. *J. Am. Chem. Soc.* **1981**, *103*, 464. Carlsen, P. H. J.; Katsuki, T.; Martin, V. S.; Sharpless, K. B. *J. Org. Chem.* **1981**, *46*, 3936.

(43) $EtAlCl_2$ and Et_2AlCl are commercially available as 25% solutions in hexane (Alfa) and toluene (Aldrich).

(44) Analysis of the reaction mixture by TLC at this stage indicated that considerable starting material (>20%) was present. Excess reagent was added to drive the reaction to completion. It was preferable to add the reagent in two batches in order to prevent olefin polymerization in the early stages of the reaction.

(1*R*,2*S*,5*R*)-2-(1-Methyl-1-phenylethyl)-5-methylcyclohexyl α-Bromoacetate (59). A solution of 629 mg (2.71 mmol) of (1*R*,2*S*,5*R*)-2-(1-methyl-1-phenylethyl)-5-methylcyclohexanol[30c] ((−)-**58**, "phenylmenthol", $[\alpha]^{25}_D$ −26.1°) in 15 mL of dry CH_2Cl_2 was treated sequentially with 236 mg (2.98 mmol) of pyridine and 576 mg (2.85 mmol) of bromoacetyl bromide at 0 °C. The mixture was warmed to room temperature and was stirred for 30 min. The reaction mixture was then diluted with 20 mL of 0.3 N HCl and was extracted with ether (3×). The combined extracts were washed with saturated $NaHCO_3$, dried (Na_2SO_4), and filtered. This solution was concentrated in vacuo to give crude **59**, which was purified by filtration through 10 g of silica gel using 150 mL of 10% ether–hexane as eluant. Evaporation of the filtrate afforded 890 mg (93%) of pure **59**: NMR (CCl_4, 60 MHz) δ 7.23 (m, 6 H), 4.82 (dt, *J* = 4, 10 Hz, 1 H), 2.94 (s, 2 H), 1.75 (m, 5 H), 1.30 (s, 3 H), 1.19 (s, 3 H), 1.02 (m, 3 H), 0.91 (d, *J* = 6 Hz, 3 H); IR (neat) 2958, 1730, 1600, 1495, 1452, 1382, 1168 cm^{-1}; the low-resolution mass spectrum showed no parent ion. High-resolution mass spectrum: calculated for $C_{18}H_{25}{}^{79}BrO_2$, 352.1038; found, 352.1026.

(1*R*,2*S*,5*R*)-2-(1-Methyl-1-phenylethyl)-5-methylcyclohexyl (*E*,*E*,*E*)-11-Methyldodeca-2,7,9-trienoate [(+)-61]. A solution of 950 mg (2.69 mmol) of bromide **59** in 3 mL of dry benzene was added dropwise to a refluxing solution of 721 mg (2.75 mmol) of triphenylphosphine in 2 mL of benzene. The resulting mixture was refluxed for 4 h and then was cooled to room temperature. Hexane (4 mL) was added whereupon a precipitate immediately separated from solution. The mother liquors were separated, and the solids were washed with an additional 4 mL of hexane. The solid residue was then dissolved in 3 mL of 1:1 H_2O–CH_3OH, to which a solution of 110 mg (2.75 mmol) of NaOH in 3 mL of H_2O was added dropwise. Two phases immediately formed. The mixture was then diluted with 5 mL of CH_2Cl_2. The aqueous phase was separated and was extracted with two additional 5-mL portions of CH_2Cl_2. The combined extracts were filtered through a cotton plug and evaporated, leaving 1.31 g (91%) of a clear amber, viscous ylid **60**. Attempts to purify **60** by crystallization were unsuccessful, and this substance was therefore used in the next step without purification.

A solution of 1.31 g (2.30 mmol, theoretical) of the above crude ylid **60** and 381 mg (2.30 mmol) of aldehyde **32** in 4 mL of dry CH_2Cl_2 was stirred overnight at room temperature. The solvent was then removed in vacuo, and the resulting solid residue was triturated with six 5-mL portions of hexane. The hexane extracts were concentrated in vacuo to give crude (+)-**61**. This compound was purified by chromatography on 40 g of silica gel using 10% ether–hexane as eluant. A 50-mL fore fraction was taken followed by forty 25-mL fractions. Fractions 6–8 contained a mixture of **61** (R_f 0.60) and the (*Z*)-dienophile isomer of **61** (R_f 0.70), while fractions 9–17 contained only **61**. The mixed fractions were rechromatographed. All in all, 39 mg of the (*Z*)-dienophile isomer (3.4%) and 652 mg (57.4%, based on bromide **59**) of pure (+)-**61** were obtained: $[\alpha]^{25}_D$ + 3.3° (*c* 0.140 g/mL, EtOH); NMR (250 MHz, $CDCl_3$) δ 7.26 (m, 5 H), 7.11 (m, 1 H), 6.51 (dt, *J* = 15.6, 6.7 Hz, 1 H), 6.00 (m, 2 H), 5.56 (m, 2 H), 5.27 (dt, *J* = 15.6, 1 Hz, 1 H), 4.84 (dt, *J* = 4.3, 10.8 Hz, 1 H), 2.32 (septet, *J* = 6.7 Hz, 1 H), 2.05 (m, 5 H), 1.93 (m, 1 H), 1.65 (m, 2 H), 1.49 (m, 3 H), 1.30 (s, 3 H), 1.21 (s, 3 H), 1.02 (m, 2 H), 1.00 (d, *J* = 6.7 Hz, 6 H), 0.85 (d, *J* = 6.5 Hz, 3 H); IR (neat) 2958, 1710, 1650, 1600, 1493, 1456, 1264, 984 cm^{-1}; a parent ion was not observed in the low-resolution mass spectrum. Anal. Calcd for $C_{29}H_{42}O_2$: C, 82.41; H, 10.02. Found: C, 82.41; H, 10.29.

(1*R*,2*S*,5*R*)-2-(1-Methyl-1-phenylethyl)-5-methylcyclohexyl (*E*,*E*)-Deca-2,7,9-trienoate [(+)-62]. A solution of 562 mg of aldehyde **29** (4.53 mmol; the crude product of DIBAL reduction of 6.51 mmol of nitrile **28**, 70% yield) and the crude ylid **60** prepared from 1.76 g (4.99 mmol) of bromide **59** in 10 mL of CH_2Cl_2 was stirred overnight at room temperature. The reaction was worked up a described for **61**. The crude product was chromatographed over 80 g of silica gel using 5% ether–hexane as eluant. An 80-mL fore frction was taken followed by 40 25-mL fractions. Fractions 17–23 yielded 82 mg (4.3%) of the (*Z*)-dienophile isomer of **62** while fractions 24–36 afforded 1.14 g (60%) of pure (+)-**62**: $[\alpha]^{22}_D$ +2.3° (*c* 0.124 g/mL, EtOH); NMR (250 MHz, $CDCl_3$) δ 7.27 (m, 5 H), 7.12 (m, 1 H), 6.51 (dt, *J* = 16.3, 6.5 Hz, 1 H), 6.32 (dt, *J* = 15.8, 9.1 Hz, 1 H), 6.06 (dd, *J* = 14.4, 15.8 Hz, 1 H), 5.67 (dt, *J* = 14.0, 6.5 Hz, 1 H), 5.27 (dt, *J* = 16.3, 1 Hz, 1 H), 5.11 (d, *J* = 14.3 Hz, 1 H), 4.99 (d, *J* = 8.1 Hz, 1 H), 4.85 (dt, *J* = 4.1, 10.9 Hz, 1 H), 2.08 (m, 4 H), 1.92 (m, 1 H), 1.66 (m, 2 H), 1.50 (m, 3 H), 1.31 (s, 3 H), 1.22 (s, 3 H), 1.04 (m, 3 H), 0.87 (d, *J* = 6.5 Hz, 3 H); IR (CH_2Cl_2) 2922, 1698, 1648, 1599, 1491, 1420, 1342, 1286, 1004, 890 cm^{-1}; a parent ion was not obbsrved in the mass spectrum. Anal. Calcd for $C_{26}H_{36}O_2$: C, 82.06; H, 9.56. Found: C, 81.97; H, 9.51.

(Menthyloxy)aluminum Dichloride Catalyzed Cyclization of 61. Triene **61** (105 mg, 0.25 mmol) was dissolved in 0.55 mL of a 0.44 M stock solution of racemic (menthyloxy)aluminum dichloride[24] (0.24 mmol) in CH_2Cl_2–toluene solution. This mixture was stirred for 48 h at room temperature[44] and then an additional 0.4 mL (0.22 mmol) of the reagent solution was added. The reaction was stirred for an additional 36 h. The reaction was then worked up a described for the (menthyloxy)aluminum dichloride catalyzed cyclization of **5**. The crude product was chromatographed on a single 1.5-mm silica gel preparative plate using 5% ether-hexane as eluant, giving 79 mg (75%) of a 33:67 (order of elution) mixture of **63B**–**63A** (GC 10 ft 5% SE-30 column, 250 °C) from the band centerd at R_f 0.55. This mixture crystallized on standing at −20 °C overnight.

Separation of 63A and 63B. A 67:33 mixture of **63A** and **63B** (GC analysis; 468 mg, the combined product from a number of cyclization experiments) was dissolved in the minimum volume of hot acetone. Acetonitrile (30 drops) and methanol (12 drops) were added. This solution was cooled to room temperature and then was seeded with a sample of the crystalline mixture of isomers. The solution was then stored at −20 °C overnight. The mother liquors were decanted, and the crystalline mass was washed with cold methanol. The crystals were dried in vacuo, giving 246 mg of a 99:1 mixture of **63A**–**63B** (GC analysis). The mother liquors (202 mg, a 23:77 mixture of **63A**–**63B**) were chromatographed on seven 0.5-mm silica gel plates using 2% ether–hexane as eluant (three developments). This resulted in a marginal separation of the two diastereomers. The lower band, R_f 0.75, afforded 157 mg of a noncrystalline 5:95 mixture of **63A**–**63B** (GC analysis). The faster moving band, R_f 0.80, afforded 45 mg of a 88:12 mixture of **63A**–**63B**. The latter sample was combined with the first crop of crystals, and the whole was then crystallized as described above giving 241 mg of isomerically pure (GC analysis) **63A** as large, transparent prisms.

Data for **63A**: mp 127–128 °C; $[\alpha]^{25}_D$ + 75.2° (*c* 0.127 g/mL, CCl_4); NMR (250 MHz, $CDCl_3$) δ 7.30 (m, 5 H), 7.17 (m, 1 H), 5.99 (br d, *J* = 10.3 Hz, 1 H), 5.59 (dt, *J* = 10.3, 1 Hz, 1 H), 4.79 (dt, *J* = 4.0, 10.7 Hz, 1 H), 2.52 (m, 2 H), 2.11 (dq, *J* = 12.0, 2.6 Hz, 1 H), 2.05–1.65 (m, 9 H), 1.50 (m, 3 H), 1.41 (s, 3 H), 1.28 (s, 3 H), 1.00 (d, *J* = 7 Hz, 3 H), 0.95 (d, *J* = 6.6 Hz, 3 H), 0.87 (d, *J* = 6.6 Hz, 3 H) IR (CH_2Cl_2) 2962, 2876, 1721, 1600, 1496, 1455, 1184, 1143, 982 cm^{-1}; no parent ion was observed in the low-resolution mass spectrum. High-resolution mass spectrum: calculated for $C_{29}H_{42}O_2$, 422.3185; found, 422.3190.

Data for **63B** (obtained on 95:5 mixture): $[\alpha]^{25}_D$ −64.4° (*c* 0.118 g/mL, CCl_4); NMR (250 MHz, $CDCl_3$) δ 7.26 (m, 5 H), 7.12 (m, 1 H), 5.92 (d, *J* = 10.3 Hz, 1 H), 5.49 (dt, *J* = 10.3, 3.3 Hz, 1 H), 4.79 (dt, *J* = 4.4, 10.7 Hz, 1 H), 2.29 (m, 1 H), 1.97 (m, 5 H), 1.60 (m, 9 H), 1.30 (s, 3 H), 1.21 (s, 3 H), 0.92 (d, *J* = 7.0 Hz, 3 H), 0.90 (d, *J* = 6.6 Hz, 3 H), 0.79 (d, *J* = 6.6 Hz, 3 H); IR (CH_2Cl_2) 2956, 2866, 1716, 1597, 1490, 1452, 1184, 1144, 982 cm^{-1}; no parent ion was observed in the low-resolution mass spectrum. High-resolution mass spectrum: calculated for $C_{29}H_{42}O_2$, 422.3185; found, 422.3194.

(Bornyloxy)aluminum Dichloride Catalyzed Cyclization of 62. A stock solution of (*l*-bornyloxy)aluminum dichloride[24b] was prepared by treating a solution of 664 mg (4.31 mmol) of *l*-borneol in 8 mL of dry CH_2Cl_2 at 0 °C with 2.42 mL (4.31 mmol) of a

1.78 M toluene solution of $EtAlCl_2$. The reaction mixture was stirred at room temperature for 2 h prior to use. Such solutions were stored at room temperature for 48 h without apparent decomposition; the reagent crystallizes at 6 °C.

A solution of 311 mg (0.82 mmol) of **62 in** 1.95 mL of the above stock solution (assumed to be 0.41 M in reagent; 0.81 mmol) was stirred for 24 h at room temperature.[44] An additional 1.0 mL (0.41 mmol) of the reagent solution was added, and the mixture was stirred for an additional 12 h. The reaction was then worked up as described for the (menthyloxy)aluminum dichloride catalyzed cyclization of **5**. The crude product was chromatographed on a 1.5-mm silica gel preparative plate using 2% ether–hexane as eluant (two developments). The band centered at R_f 0.60 was isolated, giving 256 mg (82%) of a 82:18 mixture of **64A–64B**. (This mixture was inseparable by TLC or GC. The ratio of products was determined by $LiAlH_4$ reduction of the mixture to (+)-**38**. The rotation of **38** so obtained was then compared with the rotation of isomerically pure (+)-**38** prepared from isomerically pure **64A**.) The rotation of this 82:18 mixture was $[\alpha]^{25}_D$ +18.4° (*c* 0.240 g/mL, CCl_4). This mixture crystallized when stored at 6 °C, mp 60–64 °C. Crystallization of this mixture from 1.5 mL of warm acetone containing 15 drops of CH_3CN and 10 drops of CH_3OH, with subsequent cooling to −20 °C, afforded 99 mg of crystalline product, mp 69–70 °C, $[\alpha]^{22}_D$ +39.0° (*c* 0.098 g/mL, CCl_4). This material was again recrystallized (as above), giving 67 mg of isomerically pure **64A**: mp 69–71 °C; $[\alpha]^{25}_D$ +40.6° (*c* 0.065 g/mL, CCl_4); NMR (250 MHz, $CDCl_3$) δ 7.26 (m, 5 H), 7.12 (m, 1 H), 5.76 (br d, J = 9.6 Hz, 1 H), 5.65 (m, 1 H), 4.80 (dt, J = 4.4, 10.7 Hz, 1 H), 1.31 (s, 3 H), 1.22 (s, 3 H), 0.87 (d, J = 6.6 Hz, 3 H); IR (CH_2Cl_2) 2958, 2870, 1712, ,1597, 1491, 1442, 1306, 1202, 1168, 1086, 962 cm^{-1}; no parent ion was observed in the low resolution-mass spectrum. High-resolution mass spectrum: calculated for $C_{26}H_{36}O_2$, 380.2715; found, 380.2716.

Determination of the Absolute Configurations of the Products of the Diels–Alder Cyclizations of 61 and 62. Adduct **63A** and an 82:18 mixture of **64A** and **64B** were degraded to *trans*-cyclopentane dicarboxylic acid (**42**) using the methods outlined in Scheme IV and described in detail for racemic intermediates in preceding experimental procedures. Pertinent physical data of all chiral intermediates are described below. *Please note that the absolute configuration of* (+)-***38–45*** *prepared either from* ***63A*** *or from the mixture of* ***64A*** *and* ***64B*** *are opposite to the configurations formulated in Scheme IV.*

(+)-**43** (prepared from **63A** in 93% yield): mp 28–29 °C; $[\alpha]^{25}_D$ + 170.0° (*c* 0.053 g/mL, EtOH).

(−)-**43** (prepared from 95:5 mixture of **63B–63A** in 84% yield): $[\alpha]^{25}_D$ −147.7° (*c* 0.045 g/mL, EtOH). Thus, (−)-**43** is 87% optically pure, which corresponds to a 93.5:6.5 mixture of enantiomers. This is in good agreement with the purity of **63B** determined by GC analysis.

(+)-**44**: prepared from (+)-**43** in 93% yield.

(−)-**44** (prepared from (−)-**43** in 91% yield): $[\alpha]^{25}_D$ −82.4° (*c* 0.085 g/mL, CCl_4).

(+)-**45**: prepared from (+)-**44** in 75% yield.

(+)-**41** (prepared from (+)-**45** in 40% yield): $[\alpha]^{25}_D$ +71.9° (*c* 0.016 g/mL, CCl_4).

(+)-**42** (prepared from (+)-**41** in 78% yield): mp 177–183 °C (lit.[31b] mp 181–182 °C); $[\alpha]^{25}_D$ +70.6° (*c* 0.0089 g/mL, H_2O). Evidently, some racemization occured in the hydrolysis step since a rotation of $[\alpha]^{25}_D$ +91.5° (H_2O) has previously been reported for (+)-**42**.[31b]

(+)-**38** (prepared from optically pure **64A** in 88% yield): mp 38–39 °C; $[\alpha]^{25}_D$ +45.0° (*c* 0.023 g/mL, EtOH); $[\alpha]^{25}_D$ +41.0° (*c* 0.0194 g/mL, CCl_4).

(+)-**38** (prepared from the 82:18 mixture of **64A–64B** in 85% yield): $[\alpha]^{25}_D$ +26.0° (*c* 0.086 g/mL, CCl_4), hence 63% optically pure.

(+)-**38** (prepared from the 86:14 mixture of **64A–64B** in 87% yield): $[\alpha]^{25}_D$ +28.6° (*c* 0.0102 g/mL, CCl_4), $[\alpha]^{25}_D$ +33.3° (*c* = 0.012 g/mL, EtOH), hence 72% optically pure (average of two determinations).

(+)-**38** (prepared from the 75:25 mixture of **64A–64B** in 95% yield): $[\alpha]^{25}_D$ +23.1° (*c* = 0.20 g/mL, EtOH), hence 51% optically pure.

(+)-**39** (prepared from 63% optically pure (+)-**38** in 46% yield): mp 95–97 °C; $[\alpha]^{25}_D$ +8.3° (*c* 0.082 g/mL, CCl_4).

(+)-**41** (prepared from (+)-**39** via (+)-**40** in 25% overall yield): $[\alpha]^{25}_D$ +47.9° (*c* 0.012 g/mL, CCl_4). It is interesting to note that the rotation of (+)-**41** prepared in this manner from 63% optically pure (+)-**38** is 67% that of the rotation of (+)-**41** prepared from isomerically pure (+)-**43**. This constitutes an independent check on the optical purity of these compounds.

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Registry No. (±)-**1**, 80595-21-7; (±)-**2a**, 80595-22-8; (±)-**2b**, 80595-23-9; (±)-**3**, 80595-24-0; (±)-**4**, 80641-14-1; **5**, 2409-89-4; **5** maleic anhydride Diels–Alder adduct, 74983-86-1; **6**, 74930-37-3; **7**, 74930-38-4; **9**,10-(*Z*)-**7**, 80595-25-1; **8**, 74930-39-5; (±)-**9a**, 80595-26-2; (±)-**9b**, 80595-27-3; (±)-**10a**, 80664-68-2; (±)-**10b**, 80595-28-4; (±)-**11**, 80595-29-5; (±)-**12**, 80595-30-8; (±)-**13**, 80595-31-9; (±)-**14**, 80595-32-0; (±)-**15**, 80595-33-1; (±)-**16**, 80595-34-2; (±)-**17**, 80595-35-3; (±)-**18**, 80595-36-4; **19**, 20432-40-0; **20**, 18742-02-4; (±)-**21**, 80595-37-5; **22**, 80595-38-6; **23**, 80595-39-7; (±)-**24**, 80595-40-0; **25**, 80595-41-1; (*E*)-**26**, 71779-51-6; (*Z*)-**26**, 80595-42-2; **27**, 55048-74-3; **28**, 74930-35-1; **29**, 74930-36-2; **30**, 73540-80-4; **30** acetate, 80595-43-3; **31**, 74930-45-3; **32**, 80595-44-4; (±)-**33**, 80595-45-5; (±)-**34**, 80595-46-6; (±)-**35**, 80595-47-7; (±)-**36**, 80595-48-8; (±)-**37**, 80595-49-9; (±)-**38**, 80656-10-6; (+)-**38**, 80595-50-2; (+)-**39**, 80595-51-3; (+)-**39**, 80656-11-7; (±)-**40**, 80595-52-4; (±)-**41**, 80656-12-8; (+)-**41**, 80656-13-9; (±)-**42**, 80656-14-0; (+)-**42**, 21917-20-4; (±)-**43**, 80595-53-5; (+)-**43**, 80656-15-1; (−)-**43**, 80656-16-2; (±)-**44**, 80657-41-6; (+)-**44**, 80595-54-6; (−)-**44**, 80595-55-7; (±)-**45**, 80595-56-8; (+)-**45**, 80656-17-3; (±)-**46**, 67496-01-9; (±)-**46** xanthate ester, 80595-57-9; (±)-**47**, 67496-04-2; (±)-**47** xanthate ester, 80595-58-0; (±)-**57**, 80656-18-4; (±)-**57** cyclization product, 80656-19-5; **58**, 65253-04-5; **59**, 80595-59-1; **60**, 80595-60-4; **61**, 80595-61-5; (*Z*)-**61**, 80656-20-8; **62**, 80595-62-6; (*Z*)-62, 80656-21-9; **63A**, 80657-42-7; **63B**, 80595-63-7; **64A**, 80595-64-8; **64B**, 80656-22-0; **65**, 80595-65-9; **66**, 80595-66-0; (±)-l, 80595-67-1; ((carbomethoxy)-methylene)triphenylphosphorane, 2605-67-6; bromoacetyl bromide, 598-21-0; (*o*-nitrophenyl)selenocyanate, 51694-22-5.