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Further Stereochemical Aspects of Intramolecular Diels–Alder Reactions in the Undeca-2,8,10-trienoate Ester Series[1]

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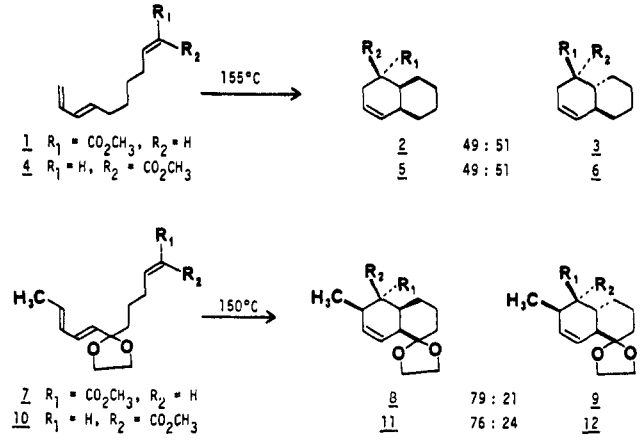
The intramolecular Diels–Alder reactions of triene esters **13** and **14** are discussed. The thermal cyclizations of these substrates were essentially stereorandom: the cyclization of **13** afforded a 50:50 mixture of **21** and **22** whereas the cyclization of **14** afforded **23** and **24** in ratio of 55:45. The Lewis acid catalyzed cyclizations, however, were much more stereoselective. The $EtAlCl_2$-promoted cyclization of **13** afforded an 88:12 mixture of **21** and **22**; the ratio of **23**/**24** from the $EtAlCl_2$-promoted cyclization of **14** was a minimum of 8:92. The results are contrasted with data previously reported for cyclizations in the perhydroindene series.

In connection with preliminary studies directed toward the total synthesis of chlorothricin we discovered that the intramolecular Diels–Alder reactions of functionalized 2,8,10-trienoate esters show a distinct preference for cis-fused products.[3,4] This preference was found to be independent of dienophile stereochemistry, with product ratios ranging from ~1:1 for the unsubstituted trienes **1** and **4** to ~3–4:1 for more highly substituted trienes such as **7** and **10** (Scheme I). We were unable, however, to assess whether the increased selectivity with **7** and **10** was related to the presence of the substituents at C-7 or C-11.[5] We were also unable to examine the influence of Lewis acid reagents on the stereoselectivity of these cyclizations owing to the sensitivity of these trienes to Lewis acid promoted decomposition reactions.[6] We comment herein on both problems using the cyclizations of **13** and **14** as a point of reference.

Scheme I



Synthesis of Trienes 13 and 14. Couping of acetate **15**[6a] with Grignard reagent **16**[3] in the presence of dilithium tetrachlorocuprate[7] afforded an 8:1 mixture of diene acetals **17a** and **17b** in 45% yield (Scheme II). This mixture, as well as the corresponding mixtures realized at the stage of aldehyde **18** and (*Z*,*E*,*E*)-triene **14**, proved to be inseparable by chromatography. Hydrolysis of the mixture of **17a** and **17b** with dilute aqueous oxalic acid afforded **18**, which condensed smoothly with (carbomethoxymethylidene)triphenylphosphorane in CH_3OH to afford a mixture of triene esters.[8] Chromatographic separation of this mixture afforded 45% of pure **13**, 5% of pure **19** and 28% of **14** contaminated to the extent of approximately 12% by the diene isomer (**20**) derived from **17b**. The presence of **20** in the samples of **14** so obtained did

(1) Taken in part from the Ph.D. Thesis of H.R.G., Massachusetts Institute of Technology, Cambridge, MA, 1982.

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(3) Roush, W. R.; Hall, S. E. *J. Am. Chem. Soc.* **1981**, *103*, 5200.

(4) Reviews of the intramolecular Diels–Alder reaction: (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.

(5) Steric interactions between groups at the opposite ends of a triene have been invoked to explain the outcome of certain intramolecular Diels–Alder reactions: Oppolzer, W.; Achini, R.; Pfenninger, E.; Weber, H. P. *Helv. Chim. Acta* **1976**, *59*, 1186. See also ref 6a.

(6) (a) Roush, W. R.; Gillis, H. R.; Ko, A. I. *J. Am. Chem. Soc.* **1982**, *104*, 2269. (b) Hall, S. E. Ph.D. Thesis, Massachusetts Institute of Technology, Cambridge, MA, 1982.

(7) (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.

(8) House, H. O.; Jones, V. K.; Frank, G. A. *J. Org. Chem.* **1964**, *29*, 3327.

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Scheme II

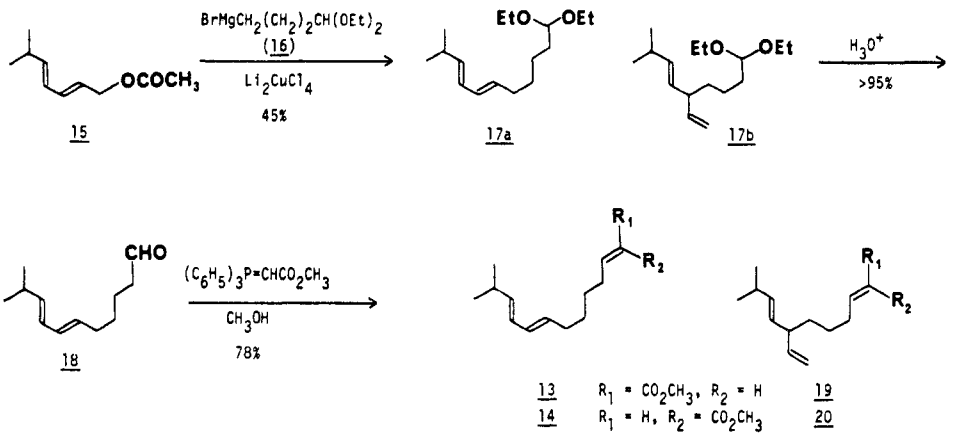
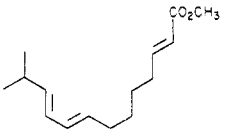
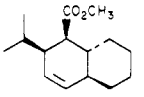
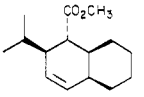
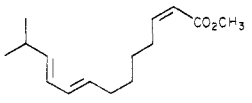
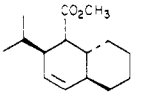
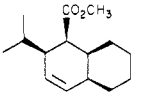


Table I[a,b]

entry	compd	reaction conditions	% yield	products	product ratio
1	 13	160 °C, 48 h	69	 21 (endo)  22 (exo)	50:50
2[c,d]	 14	180 °C, 3 h	71	 23 (exo)  24 (endo)	55:45

[a] Control experiments established that each cyclization is a kinetically controlled process. [b] Ratios of products determined by GC (18-ft DCQF-1 on Chromosorb G column, 125 °C). [c] Triene **20** (a contaminant present in **14**) was separated from cycloadducts **23** and **24** by SiO_2 chromatography. [d] See ref 10.

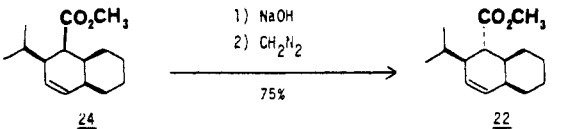
Table II

entry	triene	conditions[a]	yield, %	products	ratio[b]
1[c]	13	$EtAlCl_2$, CH_2Cl_2, 3 h	68	21/22	88:12
2[d]	13	Et_2AlCl, CH_2Cl_2, 110 h	25	21/22	88:12
3[e]	13	MenthOAlCl$_2$, CH_2Cl_2, 80 h	50	21/22	88:12
4[f,g]	14	$EtAlCl_2$, CH_2Cl_2, 4 h	77	23/24	<8:92

[a] All cyclizations were performed at 23 °C with 0.95 equiv of Lewis acid. [b] Product ratios were determined by GC using the conditions listed in Table I. Product yields refer to the yield of chromatographed product. [c] Triene **13** was recovered (6%). [d] Triene **13** was recovered (39%). [e] Triene **13** was recovered (21%). [f] Longer reaction times led to product decomposition (see ref 12a). [g] Minimum product ratio of 8:92 (see ref 12b).

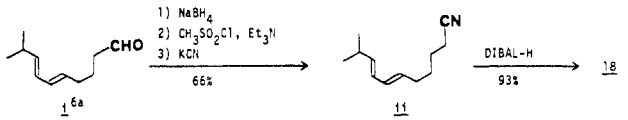
not complicate the analysis of the product mixtures realized from the thermal and Lewis acid assisted Diels–Alder reactions. This mixture, therefore, was used in the studies described in the following sections of this paper.[9]

Thermal Cyclizations. The results of the thermal cyclizations of **13** and **14** are summarized in Table I. The stereochemistry of the cycloadducts **21–24** was assigned primarily on the basis of their 250-MHz ^1H NMR spectra, for the proton α to the carbomethoxyl group (C-5H) of these compounds is diagnostic for the assigned structures.[3] For adduct **21** this signal appears as a doublet of doublets [J = 11.7, 7.3 Hz (δ 2.60)], for **22** as a triplet [J = 10.7 Hz (δ 2.68)], for **23**[10] as a doublet [J = 3.4 Hz (δ 2.54)], and for **24** as a triplet [J = 4.7 Hz (δ 2.78)]. The multiplicities of these signals are strikingly similar to those of stereochemically related cycloadducts in the perhydroindene series.[6a] These assignments are further corroborated by the observation that **24**[10] is smoothly transformed to **22** under equilibrating conditions.



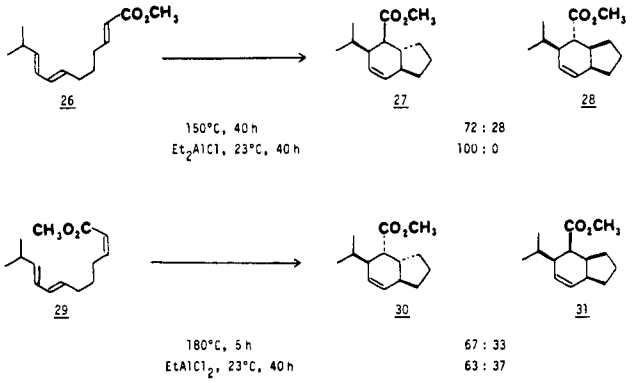
The stereoselectivities of the cyclizations of **13** and **14** parallel more closely the results reported for **1** and **4** than for **7** and **10**. We conclude, therefore, that the greater selectivity for cis-fused products exhibited by substituted undecatrienoate esters such as **7** and **10** is related to the presence of substituents at C-7 and *not* at C-11. Examination of Dreiding molecular models of the cis- and

(9) Aldehyde **18** free of the diene isomer derived from **17b** was synthesized as outlined below. Aldehyde **18** prepared in this manner, however, was not used in the present study.

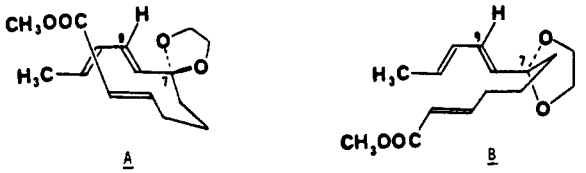


(10) The mixture of **23** and **24** obtained from the thermal cyclization of **14** could not be separated by SiO_2 chromatography. A sample of >90% pure **24** was obtained by the Lewis acid assisted cyclization of **14**. All spectroscopic data for **23** were measured on mixtures containing **24**.

Scheme III[6a]



trans-fused transition states available to **7** and **10** reveals that an eclipsing 1,3-interaction develops between the C-9 H and C-7 OR in the trans-fused transition state (A),



whereas this type of interaction is absent altogether in the cis-fused transition state (B). This interaction very well may account for the increased selectivity realized in the cyclizations of **7**, **10**, and other undecatrienoates which possess substituents at C-7.[3]

Lewis Acid Assisted Cyclizations. It was of interest to examine the effect of Lewis acids on the cyclizations of **13** and **14**.[11] As noted previously, however, attempts to cyclize **1**, **4**, or **7** in the presence of Lewis acids such as $EtAlCl_2$, Et_2AlCl, or (menthyloxy)aluminum dichloride were unsuccessful.[3,6b] Ketal **7** is very susceptible to pentadienyl carbonium ion formation (as are all diene allylic ethers), and decomposition pathways competed favorably with internal cyclization in this case. With **1** and **4**, however, the problem which precluded cyclization was the ease with which butadiene polymerization occurred. We reasoned that the latter process could be suppressed by the introduction of an alkyl substitutuent at C-11.

The results of the Lewis acid assisted cyclizations of **13** and **14** are summarized in Table II. These results show that these cyclizations are subject to catalysis with pronounced rate accelerations and significant changes in product selectivity. Ethylaluminum dichloride appears to be the best reagent for these cyclizations.

It is very interesting to note that the major product of each cyclization is the endo cycloadduct (**21** from **13** and **24** from **14**). Clearly, these catalyzed cyclizations show much higher endo selectivity than was seen in the thermal cyclizations (Table I). The behavior of **13**, therefore, parallels that of its homologue **26** in the decatriene series.[13] The behavior of **14**, however, contrasts sharply with that of **29**, which gave essentially the same distribution of products from both the thermal and Lewis acid assisted cyclizations (Scheme III). There is certainly less transition state bias in the thermal cyclizations of **13** and **14** than of **26** and **29**, and, evidently, the stereochemical course of the Lewis acid assisted cyclizations of **13** and **14** is governed largely by secondary orbital interactions. Such was not the case in the cyclization of **29** wherein increased secondary orbital control was insufficient to overcome the transition-state preference for the trans-fused product (**30**) manifested by the thermal cyclization.

These observations regarding **13** and **14** may hold interesting implications for a variety of problems in natural products synthesis.

Experimental Section

^1H NMR spectra were measured at 250 and 270 MHz on Bruker 250 and 270 instruments and at 60 MHz on Perkin-Elmer R-24B and Varian T-60 instruments. Chemical shifts are reported in δ units relative to internal Me_4Si. Infrared spectra were measured on a Perkin-Elmer Model 283B infrared spectrophotometer and were calibrated with the 1601-cm^{-1} absorption of polystyrene. Mass spectra were measured at 70 eV on a Varian MAT 44 instrument. 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 a PDP-1145 based computer system to process data recorded on photographic plates. Elemental analyses were performed by Robertson Laboratories, Florham Park, NJ. Melting points were recorded on a Fisher-Johns hot-stage melting point apparatus and are uncorrected.

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 was distilled from CaH_2; 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 performed by using activity I Woelm silica gel. All chromatography solvents were distilled prior to use.

***(E,E)*-10-Methylundeca-6,8-dienal Diethyl Acetal (17a).** Acetate **15** (1.70 g, 10.1 mmol) was dissolved in 16 mL of dry THF. The solution was cooled to −10 °C under argon, and 4.1 mL of a 0.1 M solution of Li_2CuCl_4[7c] in THF was then added. To this mixture was added Grignard reagent **16** [prepared from 3.39 g (15.1 mmol) of 4-bromobutanal diethyl acetal and 0.518 g (21.3 mmol) of magnesium turnings in 36 mL of dry THF][3] dropwise over 80 min. The reaction mixture was then stirred at 0 °C for 2.5 h and at 23 °C overnight. The mixture was then diluted with 60 mL of ether and was extracted (twice) with 25-mL portions of saturated aqueous NH_4Cl (adjusted to pH 8 with NH_4OH). The aqueous extracts were combined and back extracted (twice) with 15-mL portions of ether. The combined organic extracts were dried over Na_2SO_4 and filtered. The solvents were evaporated in vacuo to afford a clear yellow liquid. The crude product, which contained some unconsumed **15**, was dissolved in 25 mL of 3:1 CH_3OH–H_2O containing 1 N NaOH and was stirred overnight (~12 h) at 23 °C. The reaction was diluted with 20 mL of saturated aqueous $NaHCO_3$ and extracted three times with 20-mL portions of ether. The combined extracts were dried over Na_2SO_4 and filtered. The solvents were evaporated in vacuo to afford a clear yellow liquid. The crude product was purified by chromatography on 40 g of SiO_2 with 10% ether–hexane as the eluant. A 50-mL fore fraction was collected; 25-mL fractions were collected thereafter. Fractions 2–6 afforded 1.13 g (45%) of a mixture of acetals **17a,b** as a clear colorless liquid. Data for **17a**: TLC, R_f 0.5 (one development in 10% ether–hexane); ^1H NMR (60 MHz, CCl_4) δ 5.0–6.1 (m, 4 H), 4.60 (m, 1 H), 3.55 (2 q, J = 4.5 Hz, 4 H), 2.18 (m, 4 H), 1.27 (m, 16 H); IR (neat) 2960, 1636, 1460, 1371, 1343, 1122, 1060, 983 cm^{-1}. The low-resolution mass spectrum

(11) For recent examples of Lewis acid catalyzed intramolecular Diels–Alder reactions, see: (a) Funk, R. L.; Zeller, W. E. *J. Org. Chem.* **1982**, *47*, 180. (b) Stork, G.; Clark, G.; Shiner, C. S.; *J. Am. Chem. Soc.* **1981**, *103*, 4948. (c) See also ref 6a.

(12) (a) The major product **24** of the $EtAlCl_2$-promoted cyclization of **14** decomposes gradually in the presence of $EtAlCl_2$ to a mixture of two products which lack olefinic protons. These secondary products are probably the dihydro derivatives of **24** and **22**. For a related example of cycloadduct reduction by a Lewis acid see ref 6a. (b) The decomposition products of **24** coelute with **23** on the gas chromatograph. Thus, the ratio of 8:92 (**23**/**24**) determined for the $EtAlCl_2$-promoted cyclization of **14** is a lower limit for the actual product ratio.

(13) The behavior of **13** also parallels the results reported by Funk and Zeller for a case in the undeca-2,8,10-trienoate ester series.[11a]

showed no parent ion. A strong signal (12%) at m/e 208 ($M^+ - C_2H_4O$) was observed. High-resolution mass spectrum calcd for $C_{14}H_{24}O$ ($M^+ - C_2H_4O$) m/e 208.1828, found m/e 208.1794.

Two weak multiplets in the NMR spectrum of this mixture (δ 5.10 and 4.90) were assigned to the terminal vinyl protons of **17b**. This isomer was present to the extent of approximately 12% in the chromatographed product. Attempts to separate **17b** from **17a** by SiO_2 chromatography were unsuccessful.

Continued washing of the silica gel column with 250 mL of 1:1 hexane–ether afforded 0.54 g (42%) of the alcohol corresponding to acetate **15**.

(*E*,*E*)-10-Methylundeca-6,8-dienal (18). Acetal **17** (1.01 g, 4.00 mmol) was dissolved in 33 mL of DME. To this solution was added 12 mL of 5% aqueous oxalic acid, and the mixture was then stirred for 12 h at 23 °C under argon. The reaction mixture was diluted with 40 mL of saturated $NaHCO_3$ and then extracted three times with 30-mL portions of ether. The combined ether extracts were dried over Na_2SO_4 and filtered. Evaporation of the solvents in vacuo afforded aldehyde **18** as a clear pale yellow liquid: 0.720 g (100%); TLC, R_f 0.6 (one development in 10% ether–hexane); ^1H NMR (60 MHz, CCl_4) δ 9.69 (t, J = 2 Hz, 1 H), 5.0–6.1 (m, 4 H), 2.40 (m, 1 H), 2.30 (q, J = 7.0 Hz, 2 H), 2.08 (q, J = 6.5 Hz, 2 H), 1.47 (m, 4 H), 1.03 (d, J = 7.3 Hz, 6 H); IR (neat) 2960, 1726, 1651, 1457, 1372, 1096, 983 cm^{-1}; the low-resolution mass spectrum shows a parent ion at m/e 180; high-resolution mass spectrum calcd for $C_{12}H_{20}O$ m/e 180.1515, found m/e 180.1474.

Two weak multiplets in the NMR spectrum of **18** (δ 5.10 and 4.90) were assigned to the vinyl protons of the isomeric aldehyde derived from acetal **17b**, which was present as an impurity (12%) in the starting material.

Methyl (*E*,*E*,*E*)-12-Methyltrideca-2,8,10-trienoate (13) and Methyl (*Z*,*E*,*E*)-12-Methyltrideca-2,8,10-trienoate (14). Aldehyde **18** [contaminated to the extent of 12% with an isomer derived from **17b** (0.785 g, 4.36 mmol)] was dissolved in 11 mL of dry methanol. To this solution was added 1.70 g (5.23 mmol) of [(carbomethoxymethylidene)triphenyl]phosphorane. The reaction mixture was stirred for 1 h at 23 °C under argon. The solvent was evaporated in vacuo to afford a white solid mass, which was triturated ten times with 2-mL portions of hexane. The combined hexane extracts were concentrated in vacuo to yield a clear pale yellow liquid. The crude product mixture was applied to 100 g of SiO_2, and the individual products were eluted with 4% ether–hexane. A 75-mL fore fraction was collected, followed by 40 25-mL fractions. Fractions 10–14 yielded 0.290 g (28%) of a mixture of **14** and **20** (ca. 8:1, respectively). Fractions 18–24 yielded 0.463 g (45%) of *E* triene **13** as a clear colorless liquid. Fractions 16 and 17 yielded 0.043 g (4%) of **19**. The NMR and IR spectra of **19** were consistent with the assigned structure.

Data for **14**: TLC, R_f 0.8 (two developments in 5% ether–hexane); ^1H NMR (270 MHz, $DCCl_3$) δ 6.24 (dt, J = 11.2, 7.3 Hz, H_3), 5.98 (m, 2 H), 5.77 (dt, J = 11.2, 1.5 Hz, H_2), 5.55 (m, 2 H), 3.71 (s, 3 H), 2.66 (dq, J = 1.9, 7.3 Hz, 2 H, H_4), 2.31 (m, 1 H), 2.08 (q, J = 6.3 Hz, 2 H, H_7), 1.45 (m, 4 H), 1.00 (d, J = 6.8 Hz, 6 H); IR (neat) 2956, 1718, 1640, 1433, 1402, 1170, 982 cm^{-1}; the low-resolution mass spectrum shows a parent ion at m/e 236; high-resolution mass spectrum calcd for $C_{15}H_{24}O_2$ m/e 236.1776, found m/e 236.1837 (error too large); calcd for $M - CH_3OH$ m/e 204.1515, found m/e 204.1539.

Two weak signals in the NMR spectrum of **14** (δ 4.95 and 5.14) were assigned to the terminal vinyl protons of **20**. This impurity was present to the extent of approximately 12%.

Data for **13**: TLC, R_f 0.55, two developments in 5% ether–hexane; ^1H NMR (250 MHz, $DCCl_3$) δ 6.94 (dt, J = 15.4, 7.0 Hz, H_3), 5.95 (m, 2 H), 5.79 (dt, J = 15.4, 1.5 Hz, H_2), 5.55 (m, 2 H), 3.70 (s, 3 H), 2.29 (m, 1 H), 2.18 (dq, J = 1.1, 6.4 Hz, 2 H, H_4), 2.04 (q, J = 6.6 Hz, 2 H, H_7), 1.43 (m, 4 H), 0.97 (d, J = 6.6 Hz, 6 H); IR (neat) 2956, 1720, 1656, 1448, 1267, 1196, 1037 cm^{-1}. The low-resolution mass spectrum shows a weak parent ion at m/e 236. Anal. Calcd for $C_{15}H_{24}O_2$: C, 76.23; H, 10.24. Found: C, 76.48; H, 10.09.

General Procedure for the Thermal Cyclizations of Trienes 13 and 14. A solution of triene in dry toluene (at a concentration of 0.1 M or less) was transferred to a resealable Carius tube. The solution was degassed with a stream of argon. The tube was then sealed under argon 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 crude product mixtures were then analyzed by gas chromatography under the conditions indicated in footnote *b* to Table I. Cycloadducts **21** and **22**, the products from the cyclization of triene **13**, were separated by chromatography on SiO_2 preparative plates (one development in 5% ether–hexane: **21**, R_f 0.6; **22**, R_f 0.4). The yield indicated in Table I is the *combined* yield of the cyclization products. The crude mixture of products obtained from triene **14** was chromatographed on SiO_2 preparative plates (four developments in 1% ether–hexane) to afford a *mixture* (R_f 0.6) of cycloadducts **23** and **24** (free of residual triene **14** and its isomer **20**). The yield indicated in Table I is the yield of this mixture of adducts. We were not able to separate **23** and **24** by SiO_2 chromatography. Samples of **24** were obtained, in greater than 90% purity, from the Lewis acid assisted cyclization of **14**.

General Procedure for the Lewis Acid Catalyzed Cyclizations of Trienes 13 and 14. A solution of triene in dry CH_2Cl_2 (at a concentration between 0.08 and 0.1 M) was prepared. To this solution was added 0.95 equiv of the appropriate Lewis acid: $EtAlCl_2$ was added as a 1.46 M solution in hexane; Et_2AlCl was introduced as a 1.36 M solution in hexane; (menthoxy)aluminum dichloride was added as a 0.41 M solution in 3:1 CH_2Cl_2–toluene (this solution was prepared according to the procedure described in ref 6a). The reaction mixture was then stirred under argon with excess 1 N aqueous HCl and then the mixture was extracted three times with ether. The combined ether extracts were washed with a small portion of saturated aqueous $NaHCO_3$ and then dried over Na_2SO_4. The solvents were removed in vacuo and the *crude* product mixtures were then analyzed by gas chromatography (conditions as in Table I). The crude products were then purified by SiO_2 chromatography (as above for the thermal cyclizations).

Methyl 6β-(2-propyl)-1,2,3,4,4aβ,5,6,8aα-octahydronaphthalene-5β-carboxylate (21): ^1H NMR (250 MHz, $DCCl_3$) δ 5.55 (s, 2 H), 3.65 (s, 3 H), 2.60 (dd, J = 11.7, 7.3 Hz, H_5), 2.43 (m, 1 H), 1.91 (br d, J = 12.1 Hz, 1 H), 0.92 (d, J = 7.0 Hz, 3 H), 0.84 (d, J = 6.6 Hz, 3 H); IR (neat) 2922, 1733, 1650, 1444, 1364, 1255, 1212, 1159, 1133 cm^{-1}. The low-resolution mass spectrum shows a parent ion at m/e 236. Anal. Calcd for $C_{15}H_{24}O_2$: C, 76.23; H, 10.24. Found: C, 76.52; H, 9.95.

Methyl 6β-(2-propyl)-1,2,3,4,4aα,5,6,8aα-octahydronaphthalene-5α-carboxylate (22): ^1H NMR (270 MHz, $DCCl_3$) δ 5.69 (dq, J = 10.0, 1.9 Hz, 1 H), 5.42 (br d, J = 10.0 Hz, 1 H), 3.67 (s, 3 H), 2.68 (t, J = 10.7 Hz, H_5), 2.48 (br d, J = 10.2 Hz, 1 H), 2.03 (m, 2 H), 0.93 (d, J = 7.3 Hz, 3 H), 0.77 (d, J = 6.8 Hz, 3 H); IR (CH_2Cl_2) 2922, 1721, 1601, 1447, 1367, 1159, 1028 cm^{-1}. The low-resolution mass spectrum shows a parent ion at m/e 236. Anal. Calcd for $C_{15}H_{24}O_2$: C, 76.23; H, 10.24. Found: C, 76.34; H, 10.35.

Methyl 6β-(2-propyl)-1,2,3,4,4aβ,5,6,8aα-octahydronaphthalene-5β-carboxylate (24): ^1H NMR (270 MHz, $DCCl_3$) δ 5.75 (br d, J = 10.3 MHz, 1 H), 5.59 (dt, J = 10.3, 2.9 Hz, 1 H), 3.61 (s, 3 H), 2.78 (t, J = 4.7 Hz, H_5), 2.16 (m, 2 H), 1.94 (m, 1 H), 0.96 (d, J = 6.3 Hz, 3 H), 0.84 (d, J = 6.3 Hz, 3 H); IR (neat) 2910, 1734, 1637, 1429, 1371, 1153 cm^{-1}. The low-resolution mass spectrum shows a parent ion at m/e 236. Anal. Calcd for $C_{15}H_{24}O_2$: C, 76.23; H, 10.24. Found: C, 76.11; H, 9.99.

Methyl 6β-(2-propyl)-1,2,3,4,4aβ,5,6,8aα-octahydronaphthalene-5α-carboxylate (23): partial ^1H NMR data (270 MHz, $DCCl_3$) for **23** (measured on mixtures of **23** and **24** obtained from the thermal cyclization of **14**): δ 5.56 (m, 2 H, 3.62 (s, 3 H), 2.54 (d, J = 3.4 Hz, 1 H, H_5), 0.94 (d, J = 7.0 Hz, 3 H), 0.90 (d, J = 6.9 Hz, 3 H).

Epimerization of 24. Ester **24** (0.008 g, 0.034 mmol) was dissolved in 0.5 mL of DME. To this solution were added 0.75 mL of MeOH and 0.25 mL of 1 N aqueous NaOH. This mixture was stirred for 12 h at 23 °C under argon, quenched with 5 mL of 1 N aqueous HCl, and extracted three times with 5-mL portions of ether. The combined ether extracts were dried over Na_2SO_4. The solvents were filtered and then evaporated in vacuo. The residue was treated with excess ethereal CH_2N_2 for 30 min at 23 °C. The excess CH_2N was destroyed with AcOH (added dropwise until gas evolution ceased), and the reaction was then diluted with 5 mL of saturated aqueous $NaHCO_3$. This mixture was extracted three times with ether, and the combined ether extracts were dried over Na_2SO_4 and filtered. Evaporation of the solvents in vacuo afforded a pale yellow liquid. This material was applied to half

of a 0.25-mm SiO_2 preparative plate. The plate was developed once in 5% ether–hexane. A single product was isolated with ether at R_f 0.4: ester **22**, 0.006 g (75%). The high-field NMR spectrum of **22** prepared in this manner was identical with that of **22** obtained from the thermal cyclization of triene **13**.

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Registry No. **13**, 83486-81-1; **14**, 83486-82-2; **15**, 80595-43-3; **16**, 78668-96-9; **17a**, 83486-83-3; **17b**, 83486-84-4; **18**, 83486-85-5; **19**, 83486-86-6; **20**, 83486-87-7; **21**, 83486-88-8; **22**, 83486-89-9; **23**, 83486-90-2; **24**, 83486-91-3; $EtAlCl_2$, 563-43-9; Et_2AlCl, 96-10-6; $MenthOAlCl_2$, 71300-88-4; Li_2CuCl_4, 15489-27-7.

Structure and Internal Dynamics of Systems Containing Two or More *tert*-Butyl Groups in Close Proximity

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Torsional coordinates (ϕ, ϕ') for the two CC_3 rotors in 32 structural fragments of the type C_3C–C–CC_3 and *cis*-C_3C–C=C–CC_3 have been obtained from X-ray and electron diffraction data. A plot of ϕ vs. ϕ' reveals a high density of data points clustered around C_2 and, to a lesser extent, $C_{2v}(2/2)$ conformations. This distribution of points in the ϕ,ϕ' parameter space maps a minimum energy region for internal motion of the CC_3 rotors, and constitutes experimental support for the prediction that the threshold mechanism for enantiomerization of di-*tert*-butylmethane (C_2 ground state symmetry) involves correlated conrotation of the *tert*-butyl groups through a low-lying (<1 kcal mol^{-1}) transition state of $C_{2v}(2/2)$ symmetry.

Considerable interest has been shown in structural and dynamic properties of systems containing two or more *tert*-butyl groups in close proximity (Table I).[1,2] The steric strain inherent in the ground states of such compounds often leads to significant structural deformations, and the intramolecular crowding has an important effect on the internal motions of the *tert*-butyl groups.

The complete potential energy hypersurface describing torsional motions of the *tert*-butyl groups in di-*tert*-butylmethane (1) was recently calculated[2] by the empirical force field (EFF) method, using the force field from the MM2 program in conjunction with steepest descent and full-matrix Newton–Raphson geometry optimization, as implemented by the program BIGSTRN-3. A contour map with minimum energy pathways is shown in Figure 1A. There are two nonequivalent pathways that interconvert the enantiomeric (C_2) ground states. One of these requires a barrier of 0.72 kcal mol^{-1} for a transition state of $C_{2v}(2/2)$ symmetry, which is reached by synchronous conrotation of the *tert*-butyl groups. The other pathway requires a barrier of 4.86 kcal mol^{-1} for a transition state of $C_s(2/1)$ symmetry, which is reached by asynchronous disrotation of the same two groups. Both types of rotation are correlated.[3] In addition, there is a high-energy (11.86 kcal mol^{-1}) $C_{2v}(1/1)$ structure that corresponds to a partial maximum on the hypersurface.

Because of the central position of **1** as the simplest hydrocarbon representative in the class of compounds under discussion, it seemed desirable to put these calculations to an experimental test. The magnitude (0.72 kcal mol^{-1}) of the barrier calculated for the threshold mechanism, i.e., for enantiomerization by correlated conrotation, placed it outside the range of measurements accessible by dynamic NMR spectroscopy. We therefore resorted to an application of the principle of structural correlation.[5–7] This principle states[5a] that "if a correlation can be found between two or more independent parameters describing the structure of a given structural fragment in various environments, then the correlation function maps a minimum energy path in the corresponding parameter space". Static, structural information can thus be utilized to describe reaction coordinates (changes in structural parameters) for a variety of molecular processes,[5b,7] as has been amply demonstrated for association–dissociation and substitution reactions[6,8,9] and for conformational rearrangements.[5c,10–12]

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