the irreversible formation of mixture of closely related allylic cations.[12]

Conclusion

In conclusion rapid two and threefold degenerate equilibration processes were demonstrated in secondary cyclopropylcarbinyl cations which are of classical carbocation nature. In contrast the primary cyclopropylcarbinyl cations[3,4] are equilibrating nonclassical cations. The nature of classical and nonclassical ions thus cannot be differenciated in the context of static vs. equilibrating ions[14] as both of these type of ions can belong to either categories as demonstrated for example in case of studied cyclopropylcarbinyl cations.

Experimental Section

β,1-Dimethylcyclopropyl- and α,β,1-trimethylcyclopropyl methanols were prepared by the Simmons–Smith reaction on *trans*-3-penten-2-ol and *trans*-3-methyl-3-penten-2-ol in diethyl ether solutions. The *cis*-β,β′,1-trimethylcyclopropyl methanol was prepared by the addition (*cis*-β,β′-dimethylcyclopropyl)magnesium bromide to acetaldehyde in ether solution which was obtained as a mixture of isomers. The isomeric alcohols were directly used for ionization. All compounds gave satisfactory physical and spectral data.

Preparation of Carbocations. The appropriate cation precursor dissolved in SO_2ClF, precooled at −78 °C (dry ice–acetone bath temperature) is slowly added with vigrous stirring to a freshly prepared solution of a fourfold excess of SbF_5 in SO_2ClF maintained at −78 °C in a 10-mm NMR tube. This procedure affords approximately 10–15% solution of the ion.

^{13}C NMR spectroscopic studies were carried on a Varian Associates Model FT-80 spectrometer equipped with a variable-temperature broad-band probe. The chemical shifts are in parts per million from external capillary tetramethylsilane.

Acknowledgment. Support of our work by the National Science Foundation is gratefully acknowledged.

Registry No. **7**, 80243-99-8; **8**, 80244-00-4; **9**, 80244-01-5; **12**, 72610-47-0; **13**, 73882-17-4; **14**, 80244-02-6; β,1-dimethylcyclopropylcarbinol, 19293-90-4; α,β,1-trimethylcyclopropylcarbinol, 67074-42-4; β,β′,1-trimethylcyclopropylcarbinol, 80244-03-7.

(14) H. C. Brown, "The Nonclassical Ion Problem", Plenum Press, New York-London, 1977, pp 89–91.

Stereochemical Control in the Intramolecular Diels–Alder Reaction. 2. Structural and Electronic Effects on Reactivity and Selectivity

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Abstract: The cyclization reactions of a series of triene lactones activated by electron-withdrawing groups at the terminus of the chain have been investigated. The 4 + 2 cycloadducts resulting from intramolecular Diels–Alder cycloaddition were characterized and the stereochemistry determined. The effects of varying the structure of the electron-withdrawing groups and the substitution patterns of the dienophile on the rate and stereoselectivity were examined. In all cases studied, trans-hydrindene systems were produced exclusively, although the rates of the cyclization varied dramatically. This effect was interpreted on the basis of steric inhibition of resonance in the dienophile. The effects of geminal substitution in the connecting chain were also examined, and it was found that the stereochemical outcome was not altered but a rate enhancement of ~4× occurred, presumably due to a decrease in the $\Delta S^{\ddagger}$ for cyclization. This effect was interpreted in terms of a buttressing due to the geminal substitution which favorably influenced the population of conformers properly disposed to undergo cycloaddition.

The development of intramolecular analogues of electrocyclic and cycloaddition reactions as tools for the stereospecific synthesis of complex molecules has received considerable attention recently.[2,3] A number of nicely conceived examples of the use of the intramolecular Diels–Alder protocol for the preparation of complex systems have now appeared.[4] Furthermore, a growing body of data regarding the stereochemical consequences and other features of this reaction is being acquired with the intention of developing a coherent picture of the factors affecting reactivity and stereoselectivity in these processes, and of probing the scope and limitations of the process for a variety of synthetic applications.[5]

In order for the intramolecular Diels–Alder reaction to become an accepted basic strategy for the construction of complex mol-

(1) Fellow of the Alfred P. Sloan Foundation 1976–1980. Recipient of an NIH Career Development Award (Grant CA-00702). Address correspondence to this author at the University of Rochester.

(2) 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.

(3) Ciganek, E. *Org. React.*, in press.

(4) A few recent examples: (a) Snowden, R. L. *Tetrahedron Lett.* **1981**, *22*, 97, 101. (b) Wilson, S. R.; Misra, R. N. *J. Org. Chem.* **1980**, *45*, 5079. (c) Ichihara, A.; Kimura, R.; Yamada, S.; Sakamura, S. *J. Am. Chem. Soc.* **1980**, *102*, 6353. (d) Pyne, S. G.; Hensel, M. J.; Byrn, S. R.; McKenzie, A. T.; Fuchs, P. L. *Ibid.* **1980**, *102*, 5960. (e) Martin, S. F.; Tu, C.; Chou, T. *Ibid.* **1980**, *102*, 5274. (f) Taber, D. F.; Saleh, S. A. *Ibid.* **1980**, *102*, 5085. (g) Schmitthener, H. F.; Weinreb, S. M. *J. Org. Chem.* **1980**, *45*, 3372. (h) Roush, W. R.; Gillis, H. R. *Ibid.* **1980**, *45*, 4283. (i) Tietze, L.-F.; Kiedrowski, G. V. *Tetrahedron Lett.* **1981**, *22*, 219.

(5) (a) White, J. D.; Sheldon, B. G.; Solheim, B. A.; Clardy, J. *J. Org. Chem.* **1981**, *46*, 2273. (b) Nader, B.; Franck, R. W.; Weinreb, S. M. *J. Am. Chem. Soc.* **1980**, *102*, 1153. (c) Roush, W. R. *J. Org. Chem.* **1979**, *44*, 4008. (d) Roush, W. R.; Ko, A. I.; Gillis, H. R. *Ibid.* **1980**, *45*, 4264. (e) Roush, W. R.; Gillis, H. R. *Ibid.* **1980**, *45*, 4627. (f) Roush, W. R.; Peseckis, S. M. *J. Am. Chem. Soc.*, in press. (g) See also Reference 50; Roush, W. R.; Hall, S. E. *Ibid.*, in press. (h) Roush, W. R. *J. Am. Chem. Soc.* **1980**, *102*, 1390; **1978**, *100*, 3599. (i) Parker, K. A.; Adamchuk, M. R. *Tetrahedron Lett.* **1978**, 1689. (j) Oppolzer, W.; Frostl, W. *Helv. Chim. Acta* **1975**, *58*, 590. (k) Oppolzer, W. *Tetrahedron Lett.* **1974**, 1001. (l) Oppolzer, W.; Keller, K. *J. Am. Chem. Soc.* **1971**, *93*, 3836. (m) Gschwend, H. W.; Lee, A. O.; Meier, H.-P. *J. Org. Chem.* **1973**, *38*, 2169. (n) Gschwend, H. W.; Meier, H.-P. *Angew. Chem.* **1972**, *84*, 291. (o) House, H. O.; Cronin, T. H. *J. Org. Chem.* **1965**, *30*, 1061.

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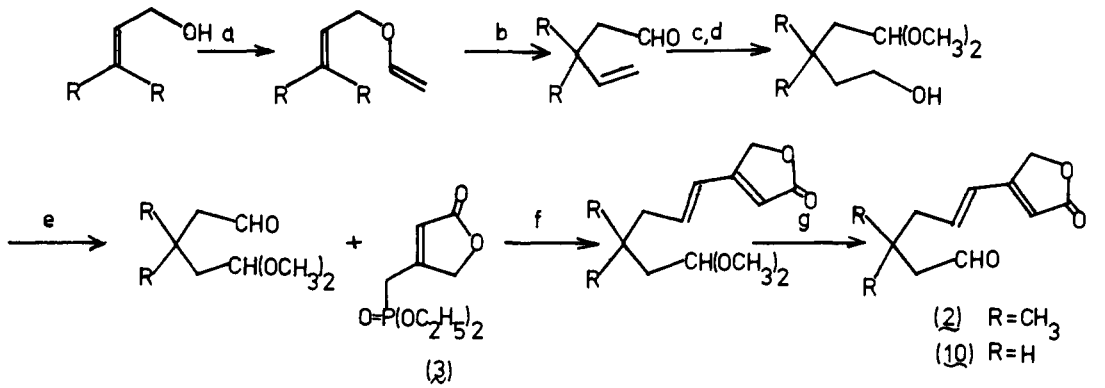
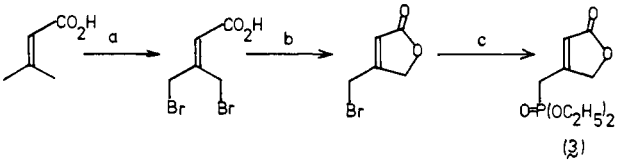
Scheme I



(a) $Hg(OAc)_2/CH_2{=}CHOC_2H_5$ (excess), Δ, 10 h; (b) reflux atmospheric pressure (~150 °C), 24 h; (c) CHOH/HCl; (d) $BH_3{\cdot}THF/H_2O_2/3$ N NaOH; (e) CrO_3-2py/CH_2Cl_2/25 °C/0.33 h; (f) NaH/DMF/-5 → 0 °C/0.5 h; (g) HCl/HOAc/0 °C

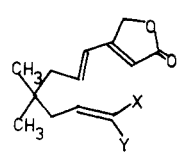
Scheme II



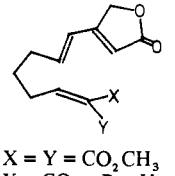
(a) NBS (2.2 equiv)/CCl_4; (b) NaOH/H_2O/25 °C; (c) $(CH_3CH_2O)_3P/\Delta$

ecules, we must answer several fundamental questions: (1) what are the limitations in terms of diene and dienophile substitution patterns upon the feasibility of the cyclization; (2) what are the structural features which primarily influence the rate of cyclization; (3) what are the structural features which primarily influence transition-state selection leading to stereoselectivity. In particular, it is of interest to differentiate the role in stereoselection of the substituents on the reacting centers from that of the atoms in the connecting chain, as well as the consequences of stereoelectronic demand due to the concerted nature of the cyclization. The potential influence of the atoms in the connecting chain on the outcome is, of course, the fundamental difference between these cyclizations and those of the much studied bimolecular process. Any theoretical treatment must permit the rationalization of observed electronic effects for both unimolecular and bimolecular processes.[6] It was our hope, in the studies described below, to begin the process of developing a model of reactivity and selectivity for the unimolecular process which would provide a reasonable level of predictive power and highlight the major differences between the unimolecular and bimolecular Diels–Alder reactions.

Preparation of the Trienes. A series of trienes were prepared of the general structure **1**. The assembly of the *Z,E* diene



4, X = Y = CO_2CH_3
5, X = CO_2CH_3, Y = CN
6, X = CO_2-*t*-Bu_2, Y = CN
7, X = Y = CN
8, X = CO_2CH_3, Y = H
9, X = CN, Y = H



11, X = Y = CO_2CH_3
12, X = CO_2-*t*-Bu, Y = CN
13, X = CO_2CH_3, Y = CN

(6) The endo rule and the concept of secondary orbital effects in transition-state selection have been the primary model utilized, cf. Onishenko, A. S. *Diene Synthesis*, "Israel Program for Scientific Translations", Jerusalem, 1964. However, even the bimolecular reaction does not strictly adhere to this model for thermal reactions: Berson, J. A.; Hamlet, Z.; Mueller, W. A. *J. Am. Chem. Soc.* **1962**, *84*, 297.
(7) Jones, G. *Org. React.* **1967**, *15*, 204.

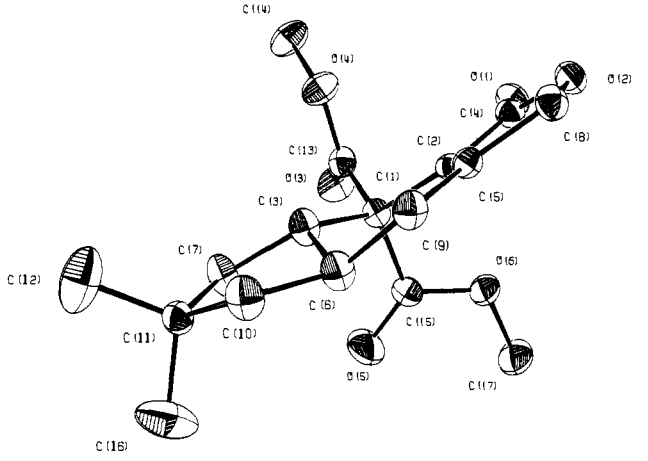


Figure 1. ORTEP plot of the final crystallographic model for **14** excluding hydrogen (R = 0.058). Numbering system is arbitrary and corresponds to that in the supplementary material.

aldehyde **2** which served as the common intermediate is shown in Scheme I. Preparation of the phosphonate **3** is given in Scheme II.

The activating groups for systems **4–7** were introduced via Knoevenagel reactions of **2** with the appropriate malonate derivative catalyzed by piperidinium acetate.[7] In the case of cyanoacetates **5** and **6**, the condensations were highly stereoselective for the *E* isomer (≥9:1).[8] The geometry of the dienophile was assigned on the basis of NMR data, which correlated with that in the literature for similar systems.[9] The β-dienophile olefinic resonance in the *E* isomers consistently appeared at lower field δ ~7.6 (t, J = 8 Hz) than the *Z* isomers (δ ~6.6–6.9).

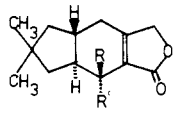
Preparation of the monosubstituted derivatives **8** and **9** was accomplished by treatment of **2** with the appropriate phosphonate reagent using the Wadsworth–Emmons procedure.[10] The desired *E* isomer was produced essentially exclusively in the case of **8** and a mixture of *E,Z* isomers (3:2) resulted for **9**, from which the desired *E* isomer was isolated by chromatography.

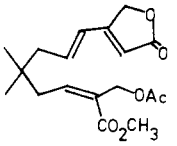
Three related triene derivatives (**11–13**), lacking the geminal methyl substitution in the connecting chain, were prepared by analogous routes via lactone aldehyde **10**.

Stereochemistry of the Cycloadditions. The first system examined was diester **4** in which the two possible transition states both situate an activating group in the supposedly favored endo orientation with respect to the diene. This system provides a test of the transition-state selection as governed by the sum of nonbonded interactions where electronic factors should be approximately comparable in both transition states.

(8) Zabicky, J. *J. Chem. Soc.* **1961**, *683*.
(9) Hayashi, T. *J. Org. Chem.* **1966**, *31*, 3253.
(10) Wadsworth, W. S., Jr. *Org. React.* **1977**, *25*, 73.

Triene diester **4** underwent smooth cycloaddition, in spite of the highly substituted diene and dienophile units, at 150 °C (0.25 h) in benzene (sealed tube) to afford a single crystalline cycloadduct (mp 133.5–135 °C). Mass spectral and NMR data established the gross structure as **14**. Surprisingly, the primary





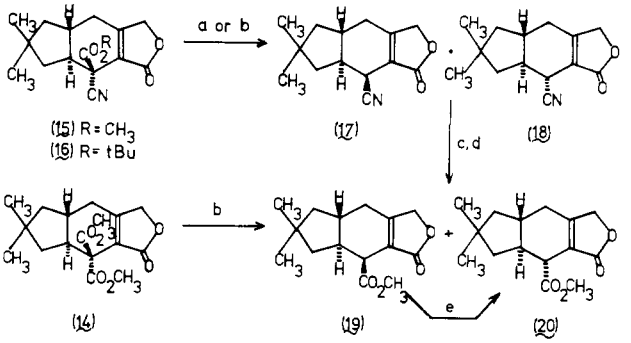
21

14, R = R' = CO_2CH_3
15, R = CN, R' = CO_2CH_3
16, R = CN, R' = CO_2-*t*-Bu
18, R = H, R' = CN
20, R = H, R' = CO_2CH_3
22, R = R' = CN

Diels–Alder adduct was not isolated, but facile double-bond migration to the tetrasubstituted lactone had occurred. This behavior provided strong circumstantial evidence for assignment of trans-ring junction stereochemistry to **14** due to the known substantially higher stability of double bonds parallel to the ring junction in trans-fused bicyclic systems.[11] Nevertheless, low-field NMR spectra were not conclusive as to ring junction stereochemistry, so a single-crystal X-ray analysis was performed on **14** which confirmed the preliminary structural assignment in all respects.[12] A computer-generated ORTEP drawing of the crystallographic model is shown in Figure 1.

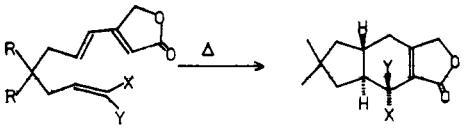
Triene **4** shows what is becoming a well-established tendency toward formation of trans-hydrindene systems.[16] This tendency was first observed by House,[5o] and concurrently with this study, Roush has described a number of examples.[5c-g] Relief of nonbonded interactions substantially favors the transition state leading to trans-fused systems. Examination of molecular models suggested that the major destabilizing interaction occurs between the allylic methylene in the dienophile and the γ-carbon of the diene as shown in eq 1.

Scheme III



(a) HCl/CH_3OH (anhydrous)/3 h/25 °C; (b) NaCN/DMF/160 °C/4 h; (c) HCl (anhydrous)/CH_3OH (anhydrous), 24 h/125 °C; (d) H_2O/25 °C; (e) $NaOCH_3/CH_3OH$/25 °C

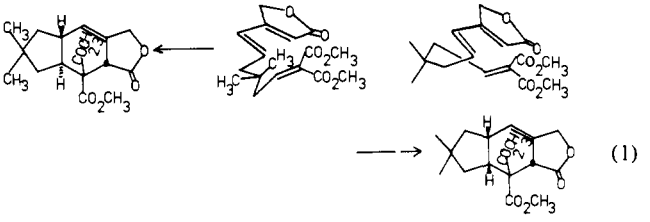
Table I



1

compd	R	X	Y	$T_{1/2}$,[a] min	$10^{-6}k$,[b] s^{-1}	k_{rel}
4	CH_3	CO_2CH_3	CO_2CH_3	222	52.04	33.6
8	CH_3	CO_2CH_3	H	702	16.46	10.6
6	CH_3	CO_2-*t*-Bu	CN	84	137.53	88.7
9	CH_3	CN	H	7740	1.55	1
7	CH_3	CN	CN	26	444.36	286.7
5	CH_3	CO_2CH_3	CN	44	262.56	169.4
11	H	CO_2CH_3	CO_2CH_3	870	13.28	8.6
13	H	CO_2CH_3	H	3780	3.06	2.1
12	H	CO_2-*t*-Bu	CN	372	31.05	20.0

[a] Determined by NMR in toluene-d_8 at 110 °C by averaged repetitive integration of appropriate olefin resonances. [b] Accuracy ±10%.



(1)

Since it was apparent that the stereochemical outcome was largely dictated by developing nonbonded interactions in the transition state, we hoped to influence the outcome by altering the relative steric demands of the two activating groups. To this end cyclization of the cyano acrylates **5** and **6** were investigated. The relatively larger steric demand of the ester group (CH_3, *t*-Bu) relative to the cyano group would, it was hoped, result in additional unfavorable nonbonded interactions in the transition state leading to trans-fused adducts. These interactions would be absent in the transition state leading to cis-fused adducts since the cyano group occupies the endo orientation. Thereby the inherent preference for the transition state leading to trans-fused adducts could be altered.

Both cyano acrylates **5** and **6** cyclized readily (110 °C/4 h/toluene), in fact, somewhat more readily than diester **4** (vide infra). In each case only a single cycloadduct was detected whose structures were assigned as **15** and **16** (mp 143–144 °C) respectively, on the basis of spectral data. Here again, complete

(11) (a) Akhrem, A. A.; Titov, Yu. A. "Total Steroid Synthesis"; Plenum Press: New York, 1970; pp. 48–50. (b) Bucourt, R. *Bull. Soc. Chim. Fr.* **1963**, 1262.

(12) Tricyclic diester lactone **14** was crystallized as needles from ethyl acetate–hexane in the monoclinic crystal class with unit cell dimensions a = 15.370 (4) Å, b = 9.399 (4) Å, c = 12.056 (4) Å, α = 90.00 (3)°, β = 97.33 (2)°, and γ = 90.00 (3)°. An approximate density of 1.06 g/cm³ was measured by flotation (calculated 1.059 g/cm³) which indicated four molecules of $C_{17}H_{22}O_5$ per unit cell. All unique data with $2\theta \leq 45°$ were collected by using graphite-monochromated Mo Kα (0.710669 Å) X-rays. A total of 2170 diffraction maxima were surveyed, and after correction for Lorentz, polarization and background effects, 1510 (69.6%), were judged observed [$F_o^2 \leq 2.50\sigma(F_o)^2$]. Systematic absences suggested the space group $P2_1/C$ and solution of the crystal structure was undertaken in this space group.[13] Signs were determined for the 230 largest normalized structure factors by using a multisolution weight sign determination process (Multan 74).[14] The most consistent set of phase relationships were determined by using the combined figures of merit (CFOM). The resulting three-dimensional E synthesis revealed 14 of the 23 nonhydrogen atoms. Successive difference electron density syntheses located the remaining nine nonhydrogen atoms. Refinement using isotropic thermal parameters for the 23 nonhydrogen atoms proceeded smoothly through three cycles. All hydrogen atoms were then included in the model at the calculated positions[15] and least-squares refinement was continued by using anisotropic thermal parameters for nonhydrogen atoms and isotropic for hydrogen atoms to a current unweighted crystallographic residual of 0.058 for observed reflections. Bond distances and bond angles generally agree well with accepted values, and no unusually close interatomic distances were noted. An ORTEP plot of the final crystallographic model is shown in Figure 1. The configuration shown is arbitrary as **14** is racemic. Additional crystallographic details may be found in the supplementary material.

(13) (a) Wilson, A. J. C. *Acta Crystallogr.* **1949**, *2*, 318. (b) Hamptmann, H.; Karle, J. *ACS Monogr.* **1953**, *No. 3*.

(14) Germain, G.; Main, P.; Woolfson, M. M. *Acta Crystallogr., Sect. A* **1971**, *A27*, 368.

(15) The following library of crystallographic programs was used: the Wayne State modifications of the W. R. Busing, K. O. Martin, and H. A. Levy program "A Fortran Crystollagraphic Least Squares Program" (USAES Report ORNL-TM-305, Oak Ridge National Laboratory, Oak Ridge, TN, 1965); the A. Zalkin program to calculate hydrogen positions, HFINDR (Lawrence Berkeley Laboratory); W. R. Busing, K. O. Martin, and H. A. Levy's "ORFFE, A Fortran Crystallographic Function and Error Program" (Report ORNL-TM-306, Oak Ridge National Laboratory, Oak Ridge, TN, 1964); M. Glick's STDDEV; C. Johnson's ORTEP ("ORTEP, A Commission Report", Report ORNL-3794, Oak Ridge National Laboratory, Oak Ridge, TN, 1965).

(16) Boeckman, R. K., Jr.; Ko, S. S. *J. Am. Chem. Soc.* **1980**, *102*, 7146.

double-bond isomerization of the primary cycloadduct had occurred, strongly suggesting that these adducts were also of the same stereochemical series as **14**.

A definitive proof of stereochemistry for **15** and **16** was undertaken as shown in Scheme III, by correlation with **14** whose structure had been established by X-ray analysis. Decarboalkoxylation of **15** and **16** by the methods indicated provided approximately the same mixture of nitriles **17** and **18** (2:1), which upon methanolysis of the nitrile provided esters **19** and **20**. The identity of **19** and **20** was established by conversion of **14** to a mixture of the same two esters **19** and **20** (1:2). The stereochemistry of **19** and **20** was confirmed by base-catalyzed interconversion of **19** and **20**.

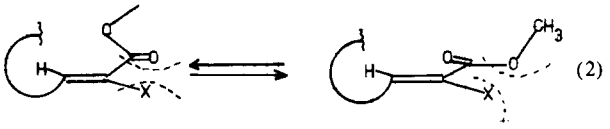
Thus with the trans stereochemistry of the adducts **15** and **16** established, it was apparent that steric demands at the terminus of the dienophile unit had little influence on the stereochemical outcome. Furthermore, as part of other studies to be described in detail later, the influence of dienophile geometry on the stereochemical outcome was examined by cyclization of triene **21**.[17] It was found that geometry of the dienophile does not dominate stereoselection by virtue of electronic effects such as secondary orbital interactions.[18] Roush has observed similar effects in a different series of trienes and has arrived at similar conclusions.[5c]

We also examined the stereochemistry of cyclization of dinitrile **7** and two *E*-disubstituted systems **8** and **9**. In the case of **7**, a single trans adduct, **22**, was obtained whose stereochemistry was assigned by analogy to that of **14**. Cyclization of **8** (155 °C/benzene/10 h) and **9** (200 °C/benzene/10 h), while significantly slower, each produced a single crystalline adduct **18** (mp 102.5–103 °C) and **20** (mp 118–119 °C), respectively. The latter proved identical with the major isomer obtained from degradation of **14** and the minor obtained from **15**/**16** (Scheme III), confirming the assignment of trans-ring junction stereochemistry.

Substituent Effects on Reactivity. Relatively few data are available in the literature regarding the effects of substitution pattern in the dienophile on the rate of cyclization of substrates via the intramolecular Diels–Alder reaction.[5m,n] Even for the bimolecular reaction, comparatively few relative rate data exist.[19] The rate of the intramolecular reaction is also profoundly influenced by the nature of the atoms in the connecting chain.[5m] We, therefore, have determined the relative rates of cyclization at 110 °C for the series of trienes **4–9** and for the series of analogues **11–13** which are devoid of the geminal methyl groups. The results are given in Table I. From the data in the literature, the reactivity pattern expected was COOR > CN, although some instances of apparent reversal are known. Therefore, it was not surprising to observe the expected relative rate difference of ~10 between **5** (CO_2CH_3) and **7** (CN). However, it is rather surprising to observe the apparent reversal of activating ability implied by the data for compounds **4–7**. To highlight the observed differences, addition of a second ester as an activating group results in a ~3.4-fold increase in rate; however, addition of CN results in an approximately 17-fold increase in rate. Even more striking is the dramatic increase in rate upon substitution of CN in **7** which results in a 287-fold increase in rate. Such apparent synergism in nitrile substitution has been reported in bimolecular Diels–Alder reactions, for example, the relative rate difference of the reaction of cyclopentadiene with acrylonitrile vs. methylene malononitrile is 4.4×10^3.[19a] A possible interpretation of these results will be discussed below.

The role of substituents on the rate is somewhat less dramatic than was anticipated. Substitution was expected to reduce the $\Delta S^{\ddagger}$ by increasing the population of conformations disposed to cyclize.[20] Comparison of systems **4** vs. **11**, **6** vs. **12**, and **8** vs. **13** shows a rate enhancement of 3.90–5.04 for the three pairs of systems examined. The internal consistency of these values over a relatively large absolute rate range and rather different functionality supports strongly the idea that the effects of the substituents have been isolated. This relative rate difference corresponds to a reduction in the entropy of activation of ~3 eu.[21]

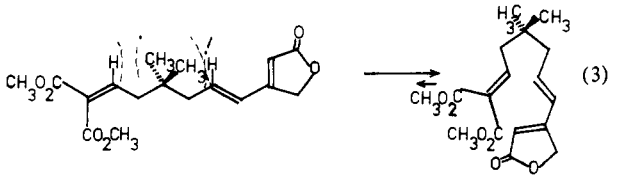
Discussion and Interpretation of the Results. The most plausible interpretation of the unusual effects on the rate of cyclization upon substitution of a cyano group revolves around the concept of steric inhibition of resonance. In order for an activating substituent to exert an effect upon the LUMO energy level of the olefin, the π systems of the olefin and activating substituent must lie approximately in a plane.[22] In the case of the ester, this requires that one of the two oxygens interact with a substituent X at the α-position of the dienophile (eq 2). When X = H, coplanarity



(2)

of either the ester (or CN) is not impeded, so the relative rates reflect those in the comparable bimolecular process in which the inherently more activating carbonyl group dominates.[23] However, upon substitution of a second ester, the steric interactions are sufficiently severe that at most one carbonyl group can be completely coplanar at any one instant. On the average, the contribution to lowering the LUMO energy of the olefin is considerably less than anticipated on the basis of complete coplanarity of both groups which is directly related to the observed diminished rate enhancement. Cyano, on the other hand, being small and axially symmetric, has no rotational requirements for overlap and at the same time produces much less disruption of the ester overlap. The bis cyanide **7** derives maximum benefit from both activating groups, thereby resulting in maximum reduction of the LUMO energy and maximum rate enhancement. It is interesting to note that increasing steric bulk in the ester has a minimal effect on rate (2×), implying that energetically these interactions are worth little in the transition state. This is consistent with the fact that the stereochemical outcome was unaltered. It is significant, however, that the decrease in activation energy resulting from substitution of cyano (~1.2 kcal/mol) is still small and insufficient to alter the stereochemical outcome. Even if this effect were felt entirely in the $\Delta S^{\ddagger}$ term, which it most certainly is not, it would be too small compared to the controlling nonbonded interactions in the connecting chain (>2.5 kcal/mol) to permit a turnover in stereochemical outcome based upon steric effects alone.

The effects of geminal substitution in the connecting chain are as anticipated on the basis of the usual effect of geminal substitution on the populations of various conformers. The buttressing (eq 3) results in an increase of the equilibrium population of cisoid



(3)

conformers which is reflected in a lowering of the $\Delta S^{\ddagger}$.[24] Typ-

(17) Boeckman, R. K., Jr.; Alessi, T. *J. Am. Chem. Soc.* submitted for publication. Cf. ref 16 also.

(18) The energetics of secondary orbital effects were approximately 1.5 kcal/mol in the case examined (cf. ref 16).

(19) (a) Sauer, J.; Wiest, H.; Mielert, A. *Chem. Ber.* **1964**, *97*, 3183. (b) Hudrlik, A. M. Ph.D. Dissertation, Columbia University, 1967. (c) Rondesvedt, C. S., Jr.; Ver Nooy, C. D. *J. Am. Chem. Soc.* **1955**, *77*, 4878.

(20) The effect of substitution on nitrogen in the studies of Gschwend[5m,n] is an example of this phenomenon.

(21) This value assumes that the $\Delta H^{\ddagger}$ for the two closely related systems is constant. We feel this is a reasonable assumption in this instance.

(22) On the basis of the UV data, twist angles of up to 30° can be accommodated with minor losses in overlap as judged by the UV extinction coefficient.

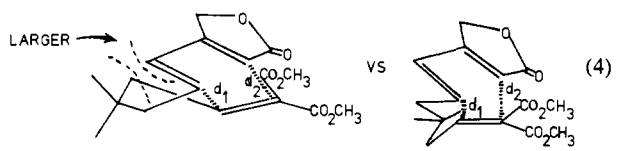
(23) The activating ability of carbonyl can be reasonably assessed by determination of relative LUMO energy levels for a series such as CN, COOR, and COR/CHO. These values (obtained by calculation) mirror the observed relative reactivities in monosubstituted olefins (cf. ref 19b): Fleming, I. "Frontier Orbitals and Organic Chemical Reactions"; Wiley: Newark, NY, 1976.

(24) (a) Allinger, N. L.; Zalkow, V. *J. Org. Chem.* **1960**, *25*, 701. (b) Dale, J. *J. Chem. Soc.* **1963**, 93. (c) See Ref 5m,n.

ically the *gem*-dialkyl effect on ring closures results in larger rate enhancements for reactions such as alkylation than those observed in our systems.[25] This may be a reflection of the fact that the buttressing provides only a small incremental change in the $\Delta S^{\ddagger}$ for a reaction which has an inherently large negative $\Delta S^{\ddagger}$.[5m]

With respect to the stereochemical results observed in this study, it is clear that the outcome depends only slightly upon dienophile substitution pattern and steric effects in the dienophile do not affect the outcome. While electronic factors are important, as will be discussed below, the endo transition state model and secondary orbital interactions do not play a dominant role in transition-state selection. The primary determinant appears to be nonbonded interactions which develop in the various diastereomeric transition states.[26] These nonbonded interactions appear to arise primarily between the carbons in the connecting chain, particularly the dienophile allylic position, and the diene unit. In the absence of other constraints, this mode of cyclizaton leads to the production of trans-hydrindene systems. Our trienes show typically better stereoselectivity than has been observed in similar systems.[5c] The reasons behind the higher level of stereoselectivity are not obvious. However, we have suggested a model which appears to rationalize this result, as well as the insensitivity of these systems to steric effects in the dienophile when the activating groups are located at the chain terminus. This model also accounts for the relatively minor role of electronic effects such as secondary orbital interactions on transition state selection.[16] These arguments apply to the thermal processes only. Catalysis of the reactions by Lewis acids would be expected to enhance the role of electronic effects in transition-state selection.[27]

Houk and Dewar have discussed the role of concerted but nonsynchronous bond formation in cycloaddition reactions,[28,29] although confirmation of this effect by calculation using high level FMO theory has not been possible.[30] Recently, White has considered a similar concept in discussing some related results.[5a] Application of this model to systems such as **14** implicates a highly unsymmetrical transition state as shown in eq 4. Significantly



(4)

larger MO coefficients in the highly polarized dienophile unit occur at the β-carbon. This polarization results in substantially advanced bonding at the β carbon in the transition state relative to the α-dienophile carbon. The geometric consequence of this unsymmetrical bonding in the transition state is that the distance d_1 is significantly less than d_2 in the transition state. Since the energetics of nonbonded interactions are extremely sensitive to changes in interatomic distances,[31] it is easy to see why nonbonded interactions between atoms in the connecting chain are magnified and therefore dominate. This model also accounts for the small observed effects of manipulation of dienophile geometry, and of steric demands of dienophile activating groups, and the diminished role of electronic effects such as secondary orbital interactions whose magnitude are also distance dependent.[32]

Further tests of this model of stereoselection are in progress and will be reported in forthcoming contributions from these laboratories, with the hope that an effective predictive model will ultimately result.

Experimental Section

Melting points were determined on a Thomas-Hoover capillary melting point apparatus and are uncorrected as are boiling points. Infrared (IR) spectra were obtained on a Perkin-Elmer 137 or Beckman Acculab IR8 and are reported in wavenumbers (cm^{-1}) by using polystyrene as standard. Nuclear magnetic resonance (NMR) spectra were recorded on either Varian T60 (60-MHz), Varian CFT-20 (80-MHz), or JEOL MH-100 (100-MHz) spectrometer. Chemical shifts are reported in parts per million (δ) downfield relative to tetramethylsilane (Me_4Si) as standard. Low-resolution mass spectra were obtained on an AEI MS-9 spectrometer, and high-resolution spectra were obtained on the CEC-21-110B high-resolution spectrometer at MIT. Data was recorded on photographic plates and processed via an IBM 1800 computer. Elemental analyses were performed by Midwest Microlab, Indianapolis, IN.

All reactions were run under an inert atmosphere of Ar or N_2 and reactions requiring anhydrous conditions were performed in flame-dried apparatus. Vigorous stirring refers to mechanical overhead stirring. Solvents and anhydrous reagents were dried according to established procedures by distillation under argon from an appropriate drying agent: benzene, ether, THF (Na/benzophenone); DME (LAH); toluene, hexane, DMF (calcium hydride); piperidine, pyridine, triethylamine (barium oxide); $CH_2Cl_2(P_2O_5)$; methanol (magnesium).

Analytical TLC was performed by using EM precoated silica gel plates (0.25 mm). Column chromatography was performed by using Baker silica gel (60–200 mesh) and medium-pressure LC (MPLC) was performed by using EM reagents silica gel (230–400 mesh).

3-Methyl-2-butenyl Vinyl Ether. A mixture of 3-methyl-2-buten-ol (74 g, 0.86 mol), mercuric acetate (6.54 g, 0.02 mol), and ethyl vinyl ether (950 mL, 716 g, 9.93 mol) was heated at reflux for 16 h under argon followed by addition of anhydrous potassium carbonate (15.4 g, 0.11 mol) to the solution after cooling to room temperature. Stirring was continued for 0.5 h, and the excess ethyl vinyl ether was removed by distillation. The residue was filtered through celite, and the solid was washed with 300 mL of pentane. The combined organic solutions were distilled under reduced pressure to give as a colorless liquid the 3-methyl-2-butenyl vinyl ether (79 g, 82%), bp 59–61 °C (100mmHg) [lit.[33] bp 114 °C (760mmHg)].

3,3-Dimethyl-4-pentenal. 3-Methyl-2-butenyl vinyl ether (73 g, 0.65 mol) was heated at reflux under argon for 24 h and cooled to room temperature to obtain the pure title aldehyde (73 g, 100%). The temperature of the reaction mixture rose gradually during the reflux period and reached 141 °C, a constant temperature after 20 h. Distillation (not normally done) could be utilized to effect further purificaton [lit.[33] bp 53 °C (56mmHg)].

1,1-Dimethoxy-3,3-dimethyl-4-pentane. 3,3-Dimethyl-4-pentenal (222 g, 1.98 mol) was dissolved in 1.2 L of absolute methanol containing about 1 g of hydrogen chloride, and the solution was stirred for 24 h at 25 °C. At the end of this period, the mixture was neutralized with solid sodium methoxide and most of the methanol was removed by distillation to concentrate the solution to about 400 mL. The residue was dissolved in ether (1.2 L) and the ethereal solution was washed with water (2 × 100 mL) and brine (100 mL), dried over $MgSO_4$, and distilled to obtain the title acetal (273 g, 87%) as a clear liquid: bp 82–84 °C (70mmHg) or 161 °C (760mmHg); IR (film) 3080, 1635, 1460, 1360, 1125, 1075, 1053 cm^{-1}; NMR ($CDCl_3$) δ 5.95 (dd, J_1 = 18 Hz, J_2 = 10 Hz, 1 H), 4.91 (dd, J_1 = 18 Hz, J_2 = 2 Hz, 1 H), 4.89 (dd, J_1 = 10 Hz, J_2 = 2 Hz, 1 H), 4.32 (t, J = 5 Hz, 1 H), 3.24 (s, 6 H), 1.55 (d, J = 5 Hz, 2 H), 1.05 (s, 6 H).

Anal. Calcd for $C_9H_{18}O_2$: C, 68.31; H, 11.47. Found: C, 68.30; H, 11.49.

3,3-Dimethyl-5,5-dimethoxypentan-1-ol. To a solution of 1,1-dimethoxy-3,3-dimethyl-4-pentene (110.6 g, 0.7 mol) in 450 mL of dry THF

(25) Typical rate accelerations are of the order of 10^2–10^3 for reactions such as alkylation (cf. ref 24).

(26) These conclusions cast doubt upon the relative importance of secondary orbital interactions as they have conventionally been illustrated and the general validity of the Alder endo model not only for intramolecular reactions being considered here but for many bimolecular thermal processes as well (cf. ref 6).

(27) It is clear, however, that catalyzed reactions favor the endo relationship of dienophile and diene, and the magnitude of secondary orbital interactions may be substantial in these instances. However, they are still of insufficient magnitude to permit cyclization of the cis dienophile in the face of unfavorable nonbonded interactions (possibly due to competing polymerization); cf. ref 5e.

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

(29) Dewar, M. J. S.; Olivella, S.; Rzepa, H. S. *J. Am. Chem. Soc.* **1978**, *100*, 5650.

(30) (a) Townsend, R. E.; Ramunni, G.; Segal, G. A.; Hehre, W. J.; Salem, L. *J. Am. Chem. Soc.* **1976**, *98*, 2190. (b) Houk, K. N. *Acc. Chem. Res.* **1975**, *8*, 361.

(31) The potential function which describes nonbonded interactions has the energy vary inversely with r^6 where r is the distance between the interacting atoms.

(32) Clearly, the magnitude of orbital interactions is also distance dependent, the greater the overlap the greater the extent of stabilization: Fleming, I. "Frontier Orbitals and Organic Chemical Reactions"; Wiley: New York, 1976; pp 27–32.

(33) (a) Cresson, P. *Bull. Soc. Chim. Fr.* **1964**, 2618. (b) Cresson, P. *Ibid.* **2629**.

at 0–5 °C (ice bath) was added a solution of diborane in THF (1 M solution, 350 mL, 0.35 mol) dropwise over a period of 2 h under argon. The ice bath was removed, and the mixture was stirred for 1.5 h at 25 °C. After the mixture was recooled to 0–5 °C, 14 mL of water was added dropwise and the mixture was stirred for 10 min to destroy the excess diborane. To this mixture was added dropwise 85 mL of 3 N NaOH solution, and stirring was continued for 15 min at 0–5 °C. An aqueous solution of hydrogen peroxide (85 mL of 30% solution) was then added, and the mixture was heated at reflux for 1.5 h under argon. After being cooled to room temperature, the mixture was diluted with ether (1.5 L) and the organic layer was separated. The aqueous layer was extracted with ether (2 × 100 mL) and the combined ether extracts were washed with brine (4 × 200 mL), dried over $MgSO_4$, and evaporated under reduced pressure. The residue was distilled under reduced pressure to afford 121 g (96%) of the title alcohol: bp 82 °C (0.5mmHg); IR (film) 3350 (s), 2900 (s), 1470, 1365, 1130 (s), 1050 (s) cm^{-1}; NMR ($CDCl_3$) δ 4.4 (t, J = 5 Hz, 1 H), 3.57 (t, J = 7 Hz, 2 H), 3.24 (s, 6 H), 2.95 (b, 1 H), 1.53 (d, J = 5 Hz, 2 H), 1.47 (t, J = 7 Hz, 2 H), 0.95 (s, 6 H).

Anal. Calcd for $C_9H_{20}O_3$: C, 61.33; H, 11.44. Found: C, 60.91; H, 11.21.

3,3-Dimethyl-5,5-dimethoxypentanal. Method A. To a stirred solution of dry pyridine (114 g, 1.2 mol) in 1.5 L of dry methylene chloride was added chromium trioxide (60 g, 0.6 mol), and the mixture was stirred for 30 min at room temperature. To the resulting burgundy solution was added a solution of the crude 3,3-dimethyl-5,5-dimethoxypentan-1-ol (0.1 mol) in 100 mL of dry methylene chloride over 5 min with vigorous stirring. After being stirred for 1 h at room temperature, the mixture was diluted with 1 L of ether. The entire mixture was filtered through a plug of Florisil to remove the chromium salts, and the filtrate (3 L) was evaporated under reduced pressure to give the crude title aldehyde. Distillation provided 13.3 g (76%, overall yield from 1,1-dimethoxy-3,3-dimethyl-4-pentene) of the pure title aldehyde; bp 92–94 °C (1.9mmHg).

Method B. To a stirred suspension of pyridinium chlorochromate (97 g, 0.45 mol) and anhydrous sodium acetate (36.9 g, 0.45 mol) in 450 mL of dry methylene chloride was added dropwise a solution of crude 3,3-dimethyl-5,5-dimethoxypentan-1-ol (0.3 mol) in 150 mL of dry methylene chloride over 10 min. The reaction mixture was stirred for 1.5 h at room temperature and then diluted with 1.5 L of ether, and the resulting suspension was stirred for 0.5 h. The entire reaction mixture was then filtered through a plug of Florisil to remove the majority of the chromium salts, and the filtrate was concentrated to about 200 mL under reduced pressure. The residue was dissolved in 500 mL of methylene chloride and washed with saturated $NaHCO_3$ solution until the aqueous layer was basic. Then it was washed with water, dried over $MgSO_4$, and evaporated under reduced pressure to give a light brown liquid residue. This residue was distilled under reduced pressure to give 36 g of the title aldehyde (69%, overall yield from 1,1-dimethoxy-3,3-dimethyl-4-pentene): IR (film) 2930(s), 2820, 2720, 1720 (s), 1470, 1385, 1365, 1120 (s), 1070 (s), 1050 (s) cm^{-1}; NMR ($CDCl_3$) δ 9.77 (t, J = 3 Hz, 1 H), 4.44 (t, J = 5 Hz, 1 H), 3.25 (s, 6 H), 2.28 (d, J = 3 Hz, 2 H), 1.63 (d, J = 5 Hz, 2 H), 1.10 (s, 6 H).

Anal. Calcd for $C_9H_{18}O_3$: C, 62.04; H, 10.41. Found: C, 61.62; H, 10.42.

3,3-Bis(bromomethyl)acrylic Acid. A solution of 3,3-dimethylacrylic acid (50 g, 0.5 mol) and *N*-bromosuccinimide (187 g, 1.05 mol) in 1 L of CCl_4 was heated to reflux and 1 g of benzoyl peroxide was added. After 2 h at reflux a second portion (0.5 g) of benzoyl peroxide was added and heating was continued for an additional 2 h. The precipitated succinimide was removed by filtration after the reaction mixture was cooled to room temperature, and the filtrate was evaporated under reduced pressure to give the crude orange-yellow oily title dibromo acid. The crude product was used for the next reaction without further purification: IR (film) 3040 (b), 1745 (s), 1635, 1415, 1265 cm^{-1}; NMR ($CDCl_3$) δ 1.18 (s, 1 H), 6.06 (s, 1 H), 4.73 (s, 2 H), 4.19 (s, 2 H).

3-(Bromomethyl)-4-hydroxy-2-butenoic Lactone. To the crude 3,3-bis(bromomethyl)acrylic acid (0.5 mol) was added dropwise 5% NaOH (20 g NaOH in 400 mL of H_2O) over 1 h, and the milky solution was stirred for 12 h at room temperature. The reaction mixture was extracted with CH_2Cl_2 (3 × 200 mL), and the combined extracts were washed with saturated $NaHCO_3$ (2 × 50 mL) and water (2 × 50 mL) and dried over $MgSO_4$. Solvents were removed by evaporation under reduced pressure to give the title bromo lactone as an orange oil (79 g, 89%). The crude product was about 90% pure as determined by NMR. Further purification was effected by distillation under reduced pressure affording the title lactone of suitable purity for the next reaction: bp 118–121 °C (0.6mmHg) [lit.[34] bp 120 °C (0.1mmHg)]: IR (film) 1775 (s), 1735 (s), 1645, 1435, 1320, 1170, 1145, 1120, 1030 (s) cm^{-1}; NMR ($CDCl_3$) δ 6.18 (m, 1 H), 5.00 (m, 2 H), 4.18 (s, 2 H).

3-[(*E*)-4,4-Dimethyl-6,6-dimethoxy-1-hexen-1-yl]-4-hydroxy-2-butenolc Lactone. Sodium hydride (56% in oil, 71.08 g, 0.165 mol) was placed in a dry 1-L three-neck flask under argon and washed free of oil with pentane (2 × 40 mL). Then 85 mL of dry DMF was introduced, and the suspension was cooled to −20 °C (CCl_4/dry ice).

A solution of the phosphonate **3** (38.71 g, 0.165 mol) in 170 mL of dry DMF was added dropwise over a 1-h period to the hydride suspension, and the mixture was stirred for 0.5 h at the same temperature. To the resulting dark red-brown solution was added dropwise a solution of the 3,3-dimethyl-5,5-dimethoxypentanal (28.8 g, 0.165 mol) during a period of 0.5 h maintaining the temperature below −10 °C. After the mixture was stirred for 0.5 h at 0 °C, the reaction was quenched by addition of 300 mL of water dropwise over 10 min. The mixture was extracted with ether (3 × 400 mL), and the combined ether extracts were washed with water (5 × 50 mL) and brine (2 × 30 mL). After being dried over $MgSO_4$, the ethereal solution was evaporated under reduced pressure and evacuated under high vacuum to give the colorless oily title diene acetal (37 g, 88%). TLC showed this material (R_f 0.38 on SiO_2 in 2:3 EtOAc–hexane) to be essentially homogeneous, and the material of this purity was normally used for the next reaction. For analytical purposes, the diene was chromatographed on silica gel with elution by 2:3 EtOAc–hexane to afford the pure title acetal as a colorless oil: IR (film) 1778 (s), 1748 (s), 1650, 1120, 1030 cm^{-1}; NMR ($CDCl_3$) δ 6.60 (d, J = 15 Hz, 1 H), 6.17 (dt, J = 15 Hz, J = 6 Hz, 1 H), 5.00 (d, J = 2 Hz, 2 H), 4.50 (t, J = 5 Hz, 1 H), 3.35 (s, 6 H), 2.20 (d, J = 6 Hz, 2 H), 1.55 (d, J = 5 Hz, 2 H), 1.00 (s, 6 H).

High-resolution mass spectrum calcd for $C_{14}H_{22}O_4$: m/e 254.151 8. Found: m/e 254.151 1.

3-(*O*,*O*-Diethylphosphonomethyl)-4-hydroxy-2-butenoic Lactone (3). Freshly distilled triethyl phosphite (39.8 g, 0.24 mol) was heated to 80 °C, and 3-(bromomethyl)-4-hydroxy-2-butenoic lactone (35.4 g, 0.2 mol) was added dropwise over a 1.5-h period under argon maintaining the internal temperature below 90 °C. The orange solution was stirred for 2 h at 90–95 °C. The byproduct ethyl bromide was distilled out of the reaction mixture during this time. The excess triethyl phosphite was removed under reduced pressure, at 95 °C, and the crude product (about 90% pure by NMR) was distilled twice (with slight decomposition) to afford over 95% pure phosphate **3** (42.1 g, 90%): bp 146–149 °C (0.05mmHg); IR (film) 2940, 2860, 1770 (s), 1750 (s), 1645, 1445, 1385, 1325, 1250 (s), 1160 (s), 1050–1020 (s), 970 (s) cm^{-1}; NMR ($CDCl_3$) 6.15 (m, 1 H), 4.97 (m, 2 H), 4.24 (q, J = 7 Hz, 4 H), 3.10 (d, J = 23 Hz, 2 H), 1.40 (t, J = 7 Hz, 6 H).

High-resolution mass spectrum calcd for $C_9H_{15}O_5P$: m/e 234.365 7. Found: m/e 234.064 0.

3-[(*E*)-4,4-Dimethyl-6-oxo-1-hexen-1-yl]-4-hydroxy-2-butenoic Lactone (2). 3,3-Dimethyl-5,5-dimethoxypentanal (37 g, 0.145 mol) was dissolved in 225 mL of acetic acid, and the solution was cooled to 0–5 °C in an ice bath. As soon as the solution started to freeze, 75 mL of 1 M HCl was added at once and the solution was stirred for 2 h in the same bath. The mixture was diluted with 1 L of chloroform and the solution washed successively with water (100 mL), saturated $NaHCO_3$ solution (until the aqueous layer was basic), and water (100 mL) and dried over anhydrous $MgSO_4$. The solvent was removed under pressure to give a colorless oily residue, and the residue was dried in vacuo to afford oily aldehyde **2** (30 g, ~100%). TLC on silica gel (2:3 EtOAc–hexane) showed a major spot at R_f 0.32 with a very minor spot R_f 0.40 and slight tailing. The aldehyde of this purity was normally used for the next reaction without further purification.

For analytical purposes, the crude aldehyde was chromatographed on silica gel with elution by 2:3 EtOAc–hexane to afford the pure aldehyde **2** as a colorless oil: IR (film) 3100, 2960, 2870, 2830, 2740, 1780 (s), 1750 (s), 1720 (s), 1650 (s), 1595, 1155, 1035 cm^{-1}; NMR ($CDCl_3$) δ 9.92 (t, J = 3 Hz, 1 H), 6.55 (d, J = 16 Hz, 1 H), 6.18 (dt, J_1 = 16 Hz, J_2 = 7 Hz, 1 H), 5.90 (t, J = 2 Hz, 1 H), 5.03 (d, J = 2 Hz, 2 H), 2.35 (d, J = 3 Hz, 2 H), 2.32 (d, J = 7 Hz, 2 H), 1.14 (s, 6 H).

High-resolution mass spectrum calcd for $C_{12}H_{16}O_3$: m/e 208.109 9. Found: m/e 208.110 3.

3-[(*E*)-7,7-Bis(methoxycarbonyl)-4,4-dimethyl-1,6-heptadien-1-yl]-4-hydroxy-2-butenoic Lactone (4). A solution of the aldehyde **2** (1.04 g, 5 mmol), dimethyl malonate (0.66 g, 5 mmol), and piperidinium acetate (0.073 g, 0.5 mmol) in 30 mL of benzene was heated at reflux under a Dean–Stark trap for 4 h. After being cooled to room temperature and diluted with 50 mL of benzene, the solution was washed with water (2 × 15 mL), dried over $MgSO_4$, and evaporated to give an oily residue of the triene **4** (1.6 g). The crude triene was chromatographed on silica gel with elution by 3:2 EtOAc–hexane to afford the pure triene **4** (1.2 g, 75%): IR (film) 3180, 1780 (s), 1750 (s), 1730 (s), 1650, 1598, 1425, 1260 (s), 1225 (s) cm^{-1}; NMR ($CDCl_3$) δ 7.08 (t, J = 8 Hz, 1 H), 6.50

(34) Martin, R.; Chapleo, C. B.; Svanholt, K. L.; Dreiding, A. S. *Helv. Chim. Acta* **1976**, *59*, 2724.

(d, J = 16 Hz, 1 H), 6.14 (dt, J_1 = 16 Hz, J_2 = 6 Hz, 1 H), 5.88 (t, J = 2 Hz, 1 H), 5.00 (d, J = 2 Hz, 2 H), 3.85 (s, 3 H), 3.82 (s, 3 H), 2.26 (d, J = 8 Hz, 2 H), 2.16 (d, J = 6 Hz, 2 H), 1.02 (s, 6 H).

High-resolution mass spectrum calcd for $C_{17}H_{22}O_6$: m/e 322.1416. Found: m/e 322.1440.

3-[(1*E*,6*E*)-7-Cyano-4,4-dimethyl-7-(methoxycarbonyl)-1,6-heptadien-1-yl]-4-hydroxy-2-butenoic Lactone (5). A solution of the aldehyde **2** (400 mg, 1.9 mmol), methyl cyanoacetate (190 mg, 1.9 mmol), piperidinium acetate (28 mg, 0.19 mmol), and anhydrous magnesium sulfate (~1 g) in 10 mL of benzene was stirred for 1 h at 60 °C, cooled, and filtered to remove the magnesium sulfate. The filtrate was diluted with 20 mL of benzene, washed with water (2 × 5 mL), dried over $MgSO_4$, and evaporated to give an oily residue of the triene **5** (550 mg). The crude triene was chromatographed on silica gel with elution by 2:3 EtOAc–hexane to afford pure triene **5** (400 mg, 73%): IR (film) 3090, 2230, 1775 (s), 1745 (s), 1260 cm^{-1}; NMR ($CDCl_3$) δ 7.74 (t, J = 8 Hz, 1 H), 6.57 (d, J = 16 Hz, 1 H), 6.17 (dt, J_1 = 16 Hz, J_2 = 6 Hz, 1 H), 5.91 (t, J = 2 Hz, 1 H), 5.03 (d, J = 2Hz, 2 H), 3.91 (s, 3 H), 2.53 (d, J = 8 Hz, 2 H), 2.24 (d, J = 6 Hz, 2 H), 1.09 (s, 6 H).

High-resolution mass spectrum calcd for $C_{16}H_{19}O_4N$: m/e 289.1314. Found: m/e 289.1328.

3-[(1*E*, 6*E*)-7-(*tert*-Butoxycarbonyl)-7-cyano-4,4-dimethyl-1,6-heptadien-1-yl]-4-hydroxy-2-butenoic Lactone (6). A solution of the aldehyde **2** (~95% pure, 30 g, 0.137 mol), *tert*-butyl cyanoacetate (19.32 g, 0.137 mol), and 1 g of piperidinium acetate in 300 mL of benzene was heated at reflux under a Dean-Stark trap at reduced pressure. The vacuum was adjusted so that the solution was at reflux at 40 °C. After 1.5 h, 1.6 mL of water was collected in the trap and there was no increase in the amount of water after additional 1.5 h. After 3 h at reflux, the mixture was cooled to room temperature, diluted with 200 mL of benzene, and washed with 0.2 N HCl (30 mL), saturated $NaHCO_3$ (20 mL), water (20 mL); and brine (20 mL). After being dried over anhydrous $MgSO_4$, the benzene solution was evaporated under reduced pressure and evacuated under high vacuum to give as a viscous oil triene **6** (44.4 g, 98%). TLC (SiO_2, 2:3 EtOAc–hexane) showed a major component at R_f 0.43 and a very minor component at R_f 0.50. Material of this purity was normally used directly in the next reaction. For analytical purposes, the triene was chromatographed on silica gel with elution by 2:3 EtOAc–hexane to afford the pure triene **6** as a colorless oil: IR (film) 3100, 2900, 2860, 2230, 1780 (s), 1750 (s), 1720 (s), 1650, 1625, 1372, 1155 (s) cm^{-1}; NMR ($CDCl_3$) δ 7.64 (t, J = 8 Hz, 1 H), 6.50 (d, J = 16 Hz, 1 H), 6.19 (dt, J_1 = 16 Hz, J_2 = 9 Hz, 1 H), 5.94 (t, J = 2 Hz, 1 H); 5.02 (d, J = 2 Hz, 2 H), 2.50 (d, J = 8 Hz, 2 H), 2.24 (d, J = 7 Hz, 2 H), 1.57 (s, 6 H).

High-resolution mass spectrum calcd for $C_{13}H_{22}O_4N$ (M – CH_3): m/e 316.1548. Found: m/e 316.1536.

3-[(*E*)-7,7-Dicyano-4,4-dimethyl-1,6-heptadien-1-yl]-4-hydroxy-2-butenoic Lactone (7). A solution of the aldehyde **2** (400 mg, 1.9 mmol), malononitrile (127 mg, 1.9 mmol), piperidinium acetate (5 mg), and anhydrous sodium sulfate (1 g) in 10 mL of benzene was stirred for 3 h at room temperature, and the entire solution was filtered through a plug of Florisil. The benzene solution was evaporated under reduced pressure to give an oily residue of the triene 9 (0.49 g, ~100%). The crude triene was chromatographed on silica gel with elution by 2:3 EtOAc–hexane to afford pure dicyanotriene **7** (0.4 g, 82%) as a colorless oil: IR (film) 3100, 2230, 1770 (s), 1740 (s), 1630, 1165 (s), 1030 (s) cm^{-1}; NMR ($CDCl_3$) δ 7.58 (t, J = 8 Hz, 1 H), 6.61 (d, J = 16 Hz, 1 H), 6.19 (dt, J_1 = 16 Hz, J_2 = 7 Hz, 1 H), 5.98 (t, J = 2 Hz, 1 H), 5.05 (d, J = 2 Hz, 2 H), 2.57 (d, J = 8 Hz, 2 H), 2.26 (d, J = 7 Hz, 2 H), 1.10 (s, 6 H).

High-resolution mass spectrum calcd for $C_{15}H_{16}O_2N_2$: m/e 256.1211. Found: m/e 256.1219.

3-[(1*E*,6*E*)-4,4-Dimethyl-7-(methoxycarbonyl)-1,6-heptadien-1-yl]-4-hydroxy-2-butenoic Lactone (8). A solution of the aldehyde **2** (1.04 g, 5 mmol) and [(carbomethoxy)methylene]triphenylphosphorane (1.67 g, 5 mmol) in 50 mL of benzene was heated at reflux for 3 h, cooled and evaporated under reduced pressure. The residue was chromatographed on silica gel with elution by 3:2 EtOAc:hexane affording pure *E,E* triene **8** (1.14 g, 87%) as a colorless oil: IR (film) 3100, 1776 (s), 1748 (s), 1722 (s), 1648, 1598, 1272 (s), 1200 (s). 1150 (s) cm^{-1}; NMR ($CDCl_3$) δ 6.98 (dt, J_1 = 15 Hz, J_2 = 7 Hz, 1 H), 6.48 (d, J = 15 Hz, 1 H), 6.12 (dt, J_1 = 15 Hz, J_2 = 6 Hz, 1 H), 5.86 (t, J = 2 Hz, 1 H), 5.48 (dt, J_1 = 15 Hz, J_2 = 1 Hz, 1 H), 5.02 (d, J = 2 Hz, 2 H), 3.64 (s, 3 H), 2.18 (d, J = 6 Hz, 2 H), 2.17 (d, J = 7 Hz, 2 H), 1.0 (s, 6 H).

High-resolution mass spectrum calcd for $C_{15}H_{20}O_4$: m/e 264.1361. Found: m/e 264.1362.

3-[(1*E*,6*E*)-7-Cyano-4,4-dimethyl-1,6-heptadien-1-yl]-4-hydroxy-2-butenoic Lactone (9) and 3-[(1*E*, 6*Z*)-7-Cyano-4,4-dimethyl-1,6-heptadien-1-yl]-4-hydroxy-2-butenoic Lactone. To a stirred suspension of sodium hydride (56%, 107 mg, 2.5 mmol, washed with 3 mL of dry hexane) in 2.5 mL of dry DMF under argon was added a solution of diethyl cyanomethylphosphonate (443 mg, 2.5 mmol) in 2.5 mL of dry DMF at 20 °C, and the solution was stirred for 30 min. A solution of the aldehyde **2** (520 mg, 2.5 mmol) in 2.5 mL of dry DMF was then added dropwise over 15 min to the anion solution, and stirring was continued for 2 h at room temperature. The reaction was quenched by slow addition of water (15 mL), and the solution was extracted with ether (2 × 50 mL). The combined ether extracts were washed with water (3 × 10 mL), dried over $MgSO_4$, and evaporated to give as an oily residue a mixture of *E* triene **9** and *Z* triene (3:2) (520 mg, 90%). The crude material was chromatographed on silica gel with elution by 2:3 EtOAc–hexane to afford pure *E* triene **9** (250 mg, 44%) and the related *Z* triene (170 mg, 29%).

***E* triene 9**: IR (film) 3095, 2215, 1778 (s), 1745 (s), 1647, 1595, 1154 (s), 1035 (s) cm^{-1} NMR ($CDCl_3$) δ 6.83 (dt, J_1 = 16 Hz, J_2 = 8 Hz, 1 H), 6.60 (d, J = 16 Hz, 1 H), 6.17 (dt, J_1 = 16 Hz, J_2 = 7 Hz, 1 H), 5.94 (t, J = 2 Hz, 1 H), 5.24 (dt, J_1 = 16 Hz, J_2 = 7 Hz, 1 H), 5.04 (d, J = 2 Hz, 2 H). 2.20 (d, J = 8 Hz, 2 H), 2.19 (d, J = 7 Hz, 2 H), 1.00 (s, 6 H).

High-resolution mass spectrum calcd for $C_{14}H_{17}O_2N$: m/e 231.1259. Found: m/e 231.1266.

***Z* triene.** IR (film) 3090, 2210, 1773 (s), 1743 (s), 1645, 1592, 1146 (s), 1025 (s) cm^{-1}; NMR ($CDCl_3$) δ 6.65 (dt, J_1 = 11 Hz, J_2 = 8 Hz, 1 H), 6.59 (d, J = 16 Hz, 1 H), 6.20 (dt, J_1 = 16 Hz, J_2 = 7 Hz, 1 H), 5.95 (t, J = 2 Hz, 1 H), 5.45 (dt, J_1 = 11 Hz, J_2 = 1.5 Hz, 1 H), 5.05 (d, J = 2 Hz, 2 H), 2.38 (dd, J_1 = 8 Hz, J_2 = 1.5 Hz, 2 H), 2.17 (d, J = 7 Hz, 2 H), 1.04 (s, 6 H).

High-resolution mass spectrum calcd for $C_{14}H_{17}O_2N$: m/e 231.1259. Found: m/e 231.1253.

5,5-Dimethoxy-1-pentanol. By the method described for the preparation of 5,5-dimethoxy-3,3-dimethyl-1-pentanol, 5,5-dimethoxy-1-pentene (19.5 g, 0.15 mol) was transformed to the title alcohol (21 g, 94%), bp 77–80 °C (0.5mmHg) [lit.[35] bp 67–69 °C (0.2mmHg)]. This material was used directly in the next reaction.

5,5-Dimethoxypentanal. By the method described for the preparation of 5,5-dimethoxy-3,3-dimethylpentanal, 5,5-dimethoxy-1-pentanol (22.2 g, 0.15 mol) was transformed to the title aldehyde (15 g, 68%, overall yield from 5,5-dimethoxy-1-pentene): bp 80–82 °C (5mmHg) [lit.[36] 57 °C (1mmHg)]; IR (film): 2740, 1735 (s), 1145 (s), 1082 (s) cm^{-1}; NMR ($CDCl_3$) δ 9.72 (t, J = 1.5 Hz, 1 H), 4.30 (t, J = 5 Hz, 1 H), 3.27 (s, 6 H), 2.44 (s (br), 2 H), 1.73–1.50 (m, 4 H).

3-[(*E*)-6,6-Dimethoxy-1-hexene-1-yl]-4-hydroxy-2-butenoic Lactone. By the method described in the preparation of 3-[(*E*)-4,4-dimethyl-6,6-dimethoxy-1-hexen-1-yl]-4-hydroxy-2-butenoic lactone, 5,5-dimethoxypentanal (7.3 g, 50 mmol) was transformed to the oily title diene lactone (7.36 g, 65%). The crude title diene was chromatographed on silica gel with elution by 4:6 EtOAc–hexane to afford 5.3 g of pure diene lactone as a colorless oil (47%): IR (film) 1775 (s), 1750 (s), 1655, 1122, 1035 cm^{-1}; NMR ($CDCl_3$) δ 6.55 (d, J = 16 Hz, 1 H), 6.16 (dt, J_1 = 16 Hz, J_2 = 6 Hz, 1 H), 5.90 (t, J = 2 Hz, 1 H), 5.01 (d, J = 2 Hz, 2 H), 4.40 (t, J = 5 Hz, 1 H), 3.37 (s, 6 H), 2.29 (q, J = 6 Hz, 2 H), 1.67–1.50 (m, 4 H).

High-resolution mass spectrum calcd for $C_{11}H_{14}O_4$ (M – CH_3OH): m/e 210.0892. Found: m/e 210.0889.

3-[(*E*)-6-Oxo-1-hexen-1-yl]-4-hydroxy-2-butenoic Lactone (10). By the method described for the preparation of the diene aldehyde **2**, 3-[(*E*)-6,6-dimethoxy-1-hexen-1-yl]-4-hydroxy-2-butenoic lactone (4 g, 17.7 mol) was transformed to the diene aldehyde **10** (3.2 g, 100%): IR (film) 3110, 2950, 2865, 2825, 2740, 1778 (s), 1745 (s), 1720 (s), 1650 (s), 1590, 1160, 1035 cm^{-1}; NMR ($CDCl_3$) δ 9.83 (t, J = 1 Hz, 1 H), 6.47 (d, J = 16 Hz, 1 H), 6.07 (dt, J_1 = 16 Hz, J_2 = 6 Hz, 1 H), 5.96 (t, J = 2 Hz, 1 H), 4.96 (d, J = 2 Hz, 2 H), 2.65–1.50 (m, 6 H).

3-[(*E*)-7,7-Bis(methoxycarbonyl)-1,6-heptadien-1-yl]-4-hydroxy-2-butenoic Lactone (11). By the method described for the preparation of the triene diester **4**, the diene aldehyde **10** (540 mg, 3 mmol) was transformed to the oily triene diester **11** (800 mg, 85%). The crude triene diester was chromatographed on silica gel with elution by 2:3 EtOAc–hexane affording pure triene ester **11** (590 g, 63%): IR (film) 1779, 1735, 1723, 1649, 1260, 1237 cm^{-1}; NMR ($CDCl_3$) δ 7.07 (t, J = 8 Hz, 1 H), 6.57 (d, J = 16 Hz, 1 H), 6.17 (dt, J_1 = 16 Hz, J_2 = 6 Hz, 1 H), 5.90 (t, J = 2 Hz, 1 H), 5.01 (d, J = 2 Hz, 2 H), 3.87 (s, 3 H), 3.83 (s, 3 H), 2.57–1.57 (m, 6 H).

High-resolution spectrum for $C_{15}H_{18}O_6$: m/e 294.1103. Found: m/e 294.1071.

3-[(1*E*,6*E*)-7-(*tert*-Butoxycarbonyl)-7-cyano-1,6-heptadien-1-yl]-4-hydroxy-2-butenoic Lactone (12). A solution of the diene aldehyde **10** (540 mg, 3 mmol), *tert*-butyl cyanoacetate (420 mg, 3 mmol), piperi-

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(36) Hattori, S. *Yuki Gosei Kagoku Kyokai Shi* **1961**, *19*, 453.

dinium acetate (6 mg), and anhydrous magnesium sulfate (500 mg) in 15 mL of dry benzene was stirred for 53 h at 25 °C, and the mixture was filtered to remove magnesium sulfate. The solvent was evaporated to give as an oily residue the crude cyanotriene ester **12** (900 mg). The crude cyanotriene ester was chromatographed on silica gel with elution by 4:6 EtOAc–hexane affording 320 mg of pure cyanotriene ester **12** (35%): IR (film) 2239, 1782, 1760, 1730, 1650, 1280, 1260, 1150 cm^{-1}; NMR ($CDCl_3$) δ 7.53 (t, J = 8 Hz, 1 H), 6.53 (d, J = 16 Hz, 1 H), 6.13 (dt, J_1 = 16 Hz, J_2 = 6 Hz, 1 H), 5.84 (t, J = 2 Hz, 1 H), 4.97 (d, J = 2 Hz, 2 H), 2.77–1.83 (m, 6 H), 1.53 (s, 9 H).

High-resolution mass spectrum calcd for $C_{16}H_{18}O_4N$ ($M - CH_3$): m/e 288.1235. Found: 288.1220.

3-[(1*E*,6*E*)-7-(Methoxycarbonyl)-1,6-heptadien-1-yl]-4-hydroxy-2-butenoic Lactone (13). A solution of the diene aldehyde **10** (540 mg, 3 mmol) and [(carbomethoxy)methylene]triphenylphosphorane (1 g, 3 mmol) in 30 mL of dry benzene was heated at reflux for 2 h, cooled, and evaporated under reduced pressure. The residue was chromatographed on silica gel with elution by 2:3 EtOAc–hexane affording pure *E* triene ester **13** (0.57 g, 80%): IR (film) 1777, 1735, 1717, 1679, 1648, 1267, 1140 cm^{-1}; NMR ($CDCl_3$) δ 6.95 (dt, J_1 = 16 Hz, J_2 = 6 Hz, 1 H), 6.50 (d, J = 16 Hz, 1 H), 6.10 (dt, J_1 = 16 Hz, J_2 = 6 Hz, 1 H), 5.84 (t, J = 2 Hz, 1 H), 5.83 (dt, J_1 = 16 Hz, J_2 = 1.5 Hz, 2 H), 4.97 (d, J = 2 Hz, 2 H), 3.73 (s, 3 H), 2.47–1.50 (m, 6 H).

High-resolution mass spectrum calcd for $C_{13}H_{16}O_4$: m/e 236.1048. Found: m/e 236.1031.

Dimethyl (1*SR*,9*RS*)-11,11-Dimethyl-4-oxo-5-oxatricyclo[7.3.0.0^{3,7}]dodec-3-ene-2,2-dicarboxylate (14). A solution of the diester triene **4** (100 mg, 0.31 mmol) and 2,6-di-*tert*-butyl-4-methylphenol (10 mg) in 2 mL of dry benzene was treated in a sealed tube at 150 °C for 15 min. The solvent was evaporated after the solution was cooled to room temperature to afford as an oily residue the adduct **14**. The crude adduct was chromatographed on silica gel with elution by 3:7 EtOAc–hexane affording pure adduct **14** as an oil (90 mg, 90%). The oily adduct was crystallized from EtOAc and hexane, and for analytical purposes the solid was recrystallized from EtOAc and hexane to 133.5–135 °C: IR ($CHCl_3$ solution) 1765 (s), 1730 (s), 1662, 1205 cm^{-1}; NMR ($CDCl_3$) δ 4.80 (s, 2 H), 3.87 (s, 3 H), 3.81 (s, 3 H), 1.12 (s, 6 H).

Anal. Calcd for $C_{17}H_{22}O_5$: C, 63.34; H, 6.88. Found: C, 62.92; H, 6.75.

Methyl (1*SR*,2*SR*,9*RS*)-2-Cyano-11,11-dimethyl-4-oxo-5-oxatricyclo[7.3.0.0^{3,7}]dodec-3-ene-2-carboxylate (15). A solution of cyano acrylate **5** (289 mg, 1.0 mmol) and 2,6-di-*tert*-butyl-4-methylphenol (10 mg) in 2 mL of dry toluene was heated at reflux for 4 h under argon. Workup by evaporation and chromatography on SiO_2 in 2:3 EtOAc–hexane afforded the adduct **15** (217 mg, 75%). **15** was recrystallized from CH_2Cl_2 to a melting point of 178.5–179.2 °C: IR (CH_2Cl_2) 2222, 1765, 1740, 1670, 1201 cm^{-1}; NMR ($CDCl_3$) δ 4.80 (s, 2 H), 3.88 (s, 3 H), 1.17 (s, 3 H), 1.14 (s, 3 H); mass spectrum, m/e 289 (P^+). Only diagnostic spectral data reported.

***tert*-Butyl (1*SR*,2*SR*,9*RS*)-2-cyano-11,11-dimethyl-4-oxo-5-oxatricyclo[7.3.0.0^{3,7}]dodec-3-ene-2-carboxylate (16).** A solution of the crude cyano acrylate **6** (44.6 g, 0.134 mol) in 200 mL of dry toluene was heated at reflux for 4 h under argon, and after the solution was cooled, the solvent was removed by evaporation under reduced pressure to obtain a viscous oily residue. The crude product was crystallized from EtOAc and hexane to afford pure crystalline adduct **16** (15.5 g). The mother liquors were chromatographed on SiO_2 (Prep LC 500) with elution by 3:7 EtOAc–hexane to obtain an additional 17 g of pure adduct **16** (32.5 g total, 63%, overall yield for four steps from 3,3-dimethyl-5,5-dimethoxypentanal). For analytical purposes, the Diels–Alder adduct **16** was recrystallized twice from EtOAc and hexane, giving **16** as white plates: mp 143–144 °C; IR ($CHCl_3$ solution) 2250, 1770 (s), 1740 (s), 1675 cm^{-1}; NMR ($CDCl_3$) δ 4.85 (s, 2 H), 1.48 (s, 9 H), 1.18 (s, 3 H), 1.15 (s, 3 H).

Anal. Calcd for $C_{19}H_{15}O_4N$: C, 68.86; H, 7.60; N, 4.23. Found: C, 69.14; H, 7.54; N, 4.10.

(1*SR*,2*RS*,9*RS*)-11,11-Dimethyl-4-oxo-5-oxatricyclo[7.3.0.0^{3,7}]dodec-3-ene-2-carbonitrile (18). A solution of monocyano triene **9** (231 mg, 1 mmol) and 2,6-di-*tert*-butyl-4-methylphenol (10 mg) in 2 mL of dry benzene was heated in a sealed tube at 200 °C for 5 h. The solvent was evaporated after the solution was cooled to room temperature to afford as an oily residue the adduct **18**. The crude product was chromatographed on silica gel with elution by 4:6 EtOAc–hexane affording pure adduct **18** as a solid. The adduct **18** was recrystallized from EtOAc and hexane to a melting point of 118–120 °C: IR (film) 2900, 2220, 1760, 1650, 1035, 1015 cm^{-1}; NMR ($CDCl_3$) δ 4.81 (s (br), 2 H), 3.67 (m, 1 H), 1.17 (s, 3 H), 1.14 (s, 3 H).

Methyl (1*SR*,2*RS*,9*RS*)-11,11-Dimethyl-4-oxo-5-oxatricyclo[7.3.0.0^{3,7}]dodec-3-ene-2-carboxylate (20). A solution of the monoester triene **8** (1 g, 3.8 mmol) and 2,6-di-*tert*-butyl-4-methylphenol (100 mg) in 10 mL of dry benzene was heated in a sealed tube at 155 °C for 1 h. The solvent was evaporated after the solution was cooled to room temperature to afford as an oily residue the adduct **20**. The crude adduct was chromatographed on silica gel with elution by 1:1 ether–hexane affording pure adduct **20** as a solid (0.85 g, 85%). The adduct **20** was recrystallized from $CHCl_3$–hexane to mp 102.5–103 °C: IR ($CHCl_3$ solution) 1755 (s), 1735 (s), 1670, 1210 cm^{-1}; NMR ($CDCl_3$) δ 4.78 (s (br), 2 H), 3.80 (s, 3 H), 1.12 (s, 6 H).

Anal. Calcd for $C_{15}H_{20}O_4$: C, 68.16; H, 7.63. Found: C, 67.89; H, 7.41.

(1*SR*, 9*RS*)-11,11-Dimethyl-4-oxo-5-oxatricyclo[7.3.0.0^{3,7}]dodec-3-ene-2,2-dicarbonitrile (22). A solution of dicyano triene **7** (256 mg, 1.0 mmol) and 2,6-di-*tert*-butyl-4-methylphenol (10 mg) in 2 mL of toluene was heated at reflux under argon for 2.5 h. Workup by evaporation of the solvent and chromatography on SiO_2 in 1:4 ethyl acetate–hexane afforded the dicyano adduct **22** (205 mg, 80%); IR 2160, 1768, 1650 cm^{-1}; NMR ($CDCl_3$) δ 4.97 (s, 2 H), 1.10 (s, 6 H); mass spectrum, m/e 256 (P^+). Only diagnostic spectral data are reported.

Decarbomethoxylation of 14 to Methyl (1*SR*,2*SR*,9*RS*)-11,11-Dimethyl-4-oxo-5-oxatricyclo[7.3.0.0^{3,7}]dodec-3-ene-2-carboxylate (19) and Methyl (1*SR*,2*RS*,9*RS*)-11,11-Dimethyl-4-oxo-5-oxatricyclo[7.3.0.0^{3,7}]dodec-3-ene-2-carboxylate (20). A solution of diester lactone **14** (100 mg, 0.31 mmol) and sodium cyanide (22 mg, 0.45 mmol) in 2 mL of anhydrous DMF was heated at reflux for 4 h. After the solution was cooled, the solvent was evaporated under high vacuum. The residue was taken up in 10 mL of $CHCl_3$ and washed with water (2 mL), dried over $MgSO_4$, and evaporated to afford an oily mixture of **19** and **20** which was purified by chromatography on SiO_2 to afford a mixture of (57 mg, 70%) of **19** and **20** (1:2) as determined by NMR (60 MHz).

The structures of **19** and **20** were confirmed by comparison of spectral and chromatographic characteristics of **20** to those of an independently prepared sample and base-catalyzed interconversion of **19** → **20**. The NMR spectral (60-MHz) characteristics of **20** were in every respect identical with that of the sample prepared independently.

Partial spectral data for **19**: IR (film) 1755 (s), 1735 (s), 1670, 1210 cm^{-1}; NMR ($CDCl_3$) δ 4.73 (s (br), 2 H), 3.70 (s, 3 H), 1.10 (s, 6 H).

Decarbomethoxylation of 15 to (1*SR*,2*SR*,9*RS*)-11,11-Dimethyl-4-oxo-5-oxatricyclo[7.3.0.0^{3,7}]dodec-3-ene-2-carbonitrile (17) and (1*SR*,2*RS*,9*RS*)-11,11-Dimethyl-4-oxo-5-oxatricyclo[7.3.0.0^{3,7}]dodec-3-ene-2-carbonitrile (18). A solution of cyano methyl ester (**15**) (95 mg, 0.33 mmol) and NaCN (23.5 mg, 0.48 mmol) in 2 mL of anhydrous DMF was treated as described previously for decarbomethoxylation of **14** to afford after chromatographic purification a mixture of nitriles **17** and **18** (48 mg, 63%) in a ratio of 2:1.

The structures of **17** and **18** were confirmed by comparison of spectral and chromatographic characteristics to **18** which was prepared independently and by conversion to a mixture of methyl esters **19** and **20** by methanolysis/hydrolysis.

Partial spectral data for **17**: IR (film) 2900, 2220, 1760, 1650, 1035 cm^{-1}; NMR ($CDCl_3$) δ 4.80 (s (br), 2 H), 3.82 (s (br), 1 H), 1.12 (s, 6 H).

Decarbo-*tert*-butoxylation of 16 to 17 and 18. A solution of *tert*-butyl cyano ester **16** (100 mg, 0.316 mmol) in 5 mL of absolute methanol was treated with gaseous HCl for 2 min and the solution stirred for 3 h at room temperature. The solution was then evaporated to dryness under reduced pressure (bath temperature = ~70 °C) to afford an oily residue. Partition of this residue between water and CH_2Cl_2, evaporation of the dried organic phase, and purification by chromatography on SiO_2 gave a mixture (57 mg, 78%) of **17** and **18** (~2:1) essentially identical with that mixture obtained by a decarbomethoxylation of **15**.

Hydrolysis of 17 and 18 to 19 and 20. A solution of mixture of **17** and **18** (~2:1) (57 mg, 0.25 mmol) in 5 mL of anhydrous CH_3OH was saturated with anhydrous HCl for 5 min, sealed, and stirred at room temperature for 48 h. After this period, solvent and HCl were removed in vacuo, and the residue was dissolved in methanol–water (2:1) and stirred for 3 h at room temperature. The mixture was diluted with 10 mL of ether, washed with brine (2 × 3 mL), dried over $MgSO_4$, and evaporated. The residue was purified by column chromatography to afford 32 mg (49%) of a mixture of esters **19** and **20** (~2:1) which were identified by comparison of their spectral characteristics and TLC mobility to the mixture of **19** and **20** derived from **14**.

Base-Catalyzed Interconversion of 19 to 20. A mixture of esters **19** and **20** (~2:1) in 1 mL of dry methanol was combined with solution of $NaOCH_3$ in CH_3OH (5 mL) prepared by dissolving sodium metal in dry methanol (~10^{-3} M). After the solution was stirred at room temperature for 24 h and heated briefly to 50 °C under argon, the solvent was evaporated and the residue was partitioned between methylene chloride and brine. The dried ($MgSO_4$) organic phase was evaporated under reduced pressure to afford a mixture of **19** and **20** (28 mg) which was analyzed by NMR to be ~1:2.

Determination of Kinetics. Kinetic experiments were conducted by heating sealed NMR tubes containing 20% (w/v) solutions of the triene substrate in toluene-d_8 (0.1 g in 0.5 mL) under Ar at 110 ± 2 °C in a constant temperature bath.

The tubes were withdrawn at intervals and cooled rapidly to room temperature in a stream of air, and the disappearance of the triene was monitored by NMR. Repetitive integration (seven to nine measurements) of an appropriate resonance (usually the β olefinic proton of the dienophile which resonated at lowest field) was utilized to establish the change in concentration of triene with time. Data points were collected through ~3 half-lives (~80% conversion) and were plotted log [triene] vs. time. All reactions showed good first-order kinetic behavior (linear plots) through ~3 half-lives. The $T_{1/2}$ and first-order rate constants were obtained from the raw data after least-squares treatment.

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Registry No. 2, 79919-74-7; **3**, 75887-42-2; **4**, 79898-46-7; **5**, 79898-47-8; **6**, 79898-48-9; **7**, 79898-49-0; **8**, 79898-50-3; **9**, 79898-51-4; **10**, 79898-52-5; **11**, 79898-53-6; **12**, 79898-54-7; **13**, 79898-55-8; (±)-**14**, 79898-56-9; (±)-**15**, 79898-57-0; (±)-**16**, 79898-58-1; (±)-**17**, 79898-59-2; (±)-**18**, 79952-31-1; (±)-**19**, 79898-60-5; (±)-**20**, 79952-32-2; (±)-**22**, 79898-61-6; 3-methyl-2-butenyl vinyl ether, 928-41-6; 3-methyl-2-buten-1-ol, 556-82-1; 3,3-dimethyl-4-pentenal, 919-93-7; 1,1-dimethoxy-3,3-dimethyl-4-pentene, 79898-62-7; 3,3-dimethyl-5,5-dimethoxypentan-1-ol, 75887-37-5; 3,3-dimethyl-5,5-dimethoxypentanal, 64600-45-9; 3,3-dibromomethylacrylic acid, 75887-43-3; 3-bromomethyl-4-hydroxy-2-butenoic lactone, 58588-90-2; 3-[(*E*)-4,4-dimethyl-6,6-dimethoxy-1-hexen-1-yl]-4-hydroxy-2-butenoic lactone, 79898-63-8; 3-[(1*E*,6*Z*)-7-cyano-4,4-dimethyl-1,6-heptadien-1-yl]-4-hydroxy-2-butenoic lactone, 79898-64-9; 5,5-dimethoxy-1-pentanol, 79898-65-0; 5,5-dimethoxypentanal, 50789-30-5; 3-[(*E*)-6,6-dimethoxy-1-hexen-1-yl]-4-hydroxy-2-butenoic lactone, 79898-66-1; 3,3-dimethylacrylic acid, 541-47-9; ethyl vinyl ether, 109-92-2; dimethyl malonate, 108-59-8; methyl cyanoacetate, 105-34-0; *tert*-butyl cyanoacetate, 1116-98-9; malonitrile, 109-77-3; carbomethoxymethylene triphenylphosphorane, 2605-67-6; diethyl cyanomethylphosphonate, 2537-48-6; 5,5-dimethoxy-1-pentene, 14152-71-7.

Supplementary Material Available: Tables of fractional coordinates, bond angles, and distances for diester lactone **14**, and an ORTEP drawing of **14** (4 pages). Order information is given on any current masthead page.

Chemiluminescence of Organic Peroxides. Thermal Generation of an *o*-Xylylene Peroxide[1]

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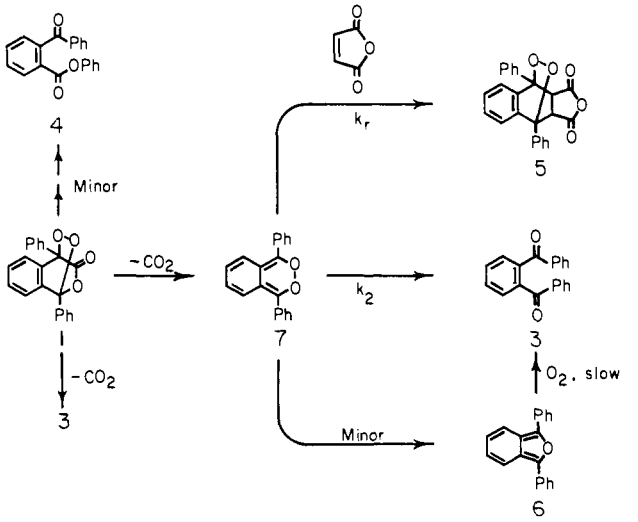
Abstract: Thermolysis of 1,4-diphenyl-1,4-dioxa-2,3-benzopyrone (endoperoxide **1**) in *p*-xylene solution generates chemiluminescence. Three products are formed from thermolysis of **1**. The major product, trapped in 70% yield by added maleic anhydride, is 1,4-diphenyl-2,3-benzodioxin (*o*-xylylene peroxide **7**). This peroxide eventually becomes *o*-dibenzoylbenzene **3** which is isolated from the reaction in 85% yield. The two other products, 1,3-diphenylisobenzofuran (**6**) and phenyl *o*-benzoylbenzoate (**4**), are isolated in yields of ca. 2% and 5%, respectively. The observed chemiluminescence results from interaction of **7** with an added fluorescent activator or with the product 1,3-diphenylisobenzofuran according to the chemically initiated electron-exchange luminescence (CIEEL) mechanism.

The molecules and mechanisms responsible for chemiluminescence and bioluminescence have been of considerable interest to chemists since the dawn of the science.[2] Much recent interest in this topic has centered on the thermal chemistry of organic peroxides.[3] Our efforts to discover new chemiluminescent systems and to probe the mechanism of electronically excited state generation led to the synthesis and investigation of new heterocyclic examples of this functional group. In this report we describe the preparation, characterization, and thermal reactions of endoperoxide **1**. The properties of this molecule provide further insight into the chemistry of organic peroxides and into the mechanistic details of chemiluminescence.

Results and Discussion

Synthesis. The preparation of endoperoxide **1** proceeds straightforwardly by photooxygenation of the previously described lactone **2**.[4] Irradiation of an acetone solution of **2** and methylene blue with visible light, filtered so that only the sensitizer is excited, at 0 °C under O_2 leads to the rapid consumption of the lactone. Removal of the sensitizer by filtration through silica gel, evaporation of the solvent, and recrystallization of the resulting residue gives a peroxidic white solid. The structure of this material was deduced from spectroscopic, osmometric, and microanalytic investigation to be endoperoxide **1** (eq 1). The details of the

Scheme 1



† Fellow of the Alfred P. Sloan Foundation (1977-1979) and the Dreyfus Foundation (1979-1984).

(1) Smith, J. P.; Schuster, G. B. *J. Am. Chem. Soc.* **1978**, *100*, 2564.

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