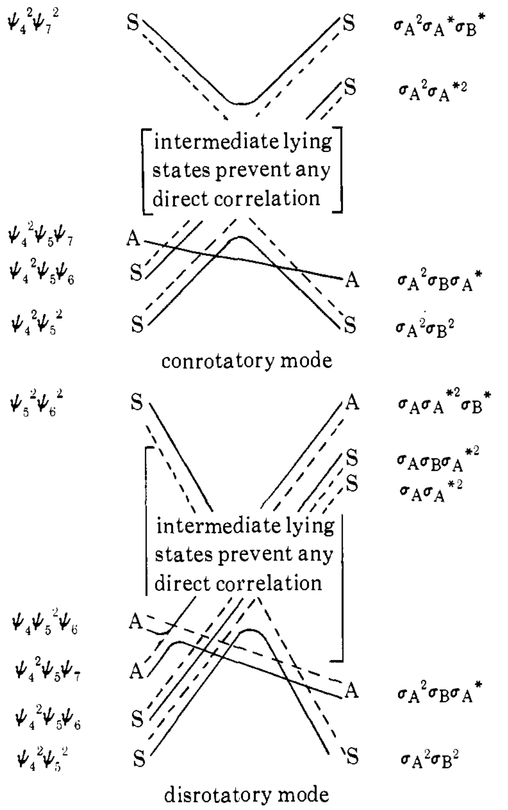
Chart IX. State Correlation Diagram for Reaction I′



ring has altered the products allowed for this reaction from those allowed for the unsubstituted case.

(4) **N-Substituted 2,2′-Divinylbiphenyl.** All the symmetrical tetranitrogen-substituted molecules follow the same pattern as the unsubstituted molecule in part 2 (molecules with adjacent nitrogens were not considered). This pattern also holds for three of the four symmetrical dinitrogen-substituted molecules (4,13-N was not done).

II. Conclusions

Perhaps the most significant point is that the *dielectrocyclic* classification of reactions of the type illustrated in Schemes I and II can, *in principle*, yield more unique information than a simple cycloaddition classification. It is apparent that the use of state correlation diagrams is essential in this treatment and that care must be exercised to ensure that the omission of intermediate states does not materially alter the conclusions. It is also apparent that in some cases the cyclized product states "favored" by the correlation diagram may be relatively unstable if they contain antibonding σ orbitals. Finally, it appears that perturbations in the ring can affect significantly the cyclization and hence a simple 2 + 2 cycloaddition classification is questionable. Hence, it appears possible to change the course and consequently the stereospecificity of reaction by heteroatom substitution at a site well removed from the reaction region.

Acknowledgments. The award of a National Research Council Scholarship to one of us (ECWS) is gratefully acknowledged. Several interesting discussions of this problem with Dr. D. F. Tavares and Dr. R. P. Haseltine are also acknowledged.

Synthesis and Interconversions of $(CH)_{12}$ Hydrocarbons

Leo A. Paquette* and John C. Stowell[1]

Contribution from the Department of Chemistry, The Ohio State University, Columbus, Ohio 43210. *Received February 3, 1971*

Abstract: The cycloaddition of cyclobutadiene to a cis,trans mixture of 7,8-dichlorobicyclo[4.2.0]octa-2,4-diene gives a separable mixture of *cis*- and *trans-exo,exo*-3,4-dichlorotetracyclo[4.4.2.0^{2,5}.0^{7,10}]dodeca-8,11-dienes. Treatment of these dichlorides with sodium phenanthrene gives *exo,exo*-tetracyclo[4.4.2.0^{2,5}.0^{7,10}]dodecatriene, which on pyrolysis at 500° affords *exo*-tricyclo[4.4.2.0^{7,10}]dodecatetraene (**15**). This last hydrocarbon is shown to be identical with the product of thermal rearrangement of *cis,syn,cis*-tricyclo[8.2.0.0^{2,9}]dodeca-3,5,7,11-tetraene (**3**). In ether, irradiation of **15** provides an equimolar mixture of *exo,exo*- and *exo,endo*-tetracyclo[4.4.2.0^{2,5}.0^{7,10}]dodecatrienes (**14** and **16**); under triplet conditions, however, **15** affords principally tetracyclo[5.3.2.0^{2,5}.0^{6,8}]dodeca-3,9,11-triene (**4**). Partial decomposition of **14** and **16** at 500° revealed that **14** rearranges somewhat more rapidly than **16**; the latter undergoes rearrangement exclusively to give **15**. The mechanistic aspects of these $(CH)_{12}$ interconversions, as well as the thermal behavior of the 3-methyl and 3-chloro derivatives of **14**, are discussed.

The isomeric $(CH)_{12}$ hydrocarbons represent an interesting family of compounds because of the theoretical significance of many of its members and the varied electrocyclic and sigmatropic processes expected of the numerous valence tautomers. Despite these attractive features, chemical investigation in this area has been limited because of the relative unavailability of synthetic entries to these polyenes. For these reasons, we have been interested in the possibility of developing facile and stereochemically controlled syntheses of several $(CH)_{12}$ isomers.

Prior to this investigation, access to the few known $(CH)_{12}$ hydrocarbons has been gained solely by way of the cyclooctatetraene dimers **1** and **2**.[2–6] Both dimers

---

[1] National Institutes of Health Postdoctoral Fellow, 1969–1970; The Ohio State University Postdoctoral Fellow, 1969.

[2] [12]Annulene, the monocyclic member of the $(CH)_{12}$ series has recently been synthesized: J. F. M. Oth, H. Rottele, and G. Schröder,

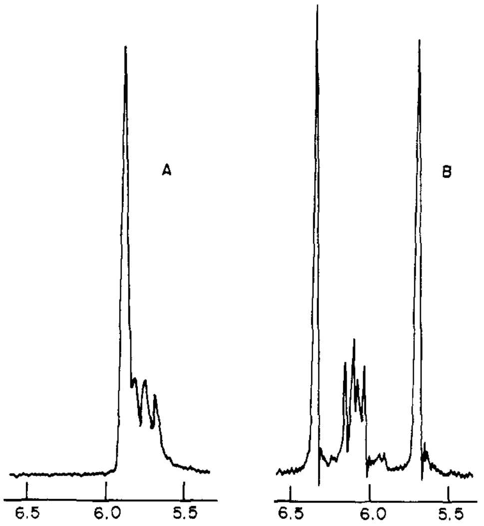
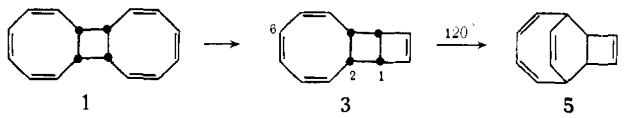
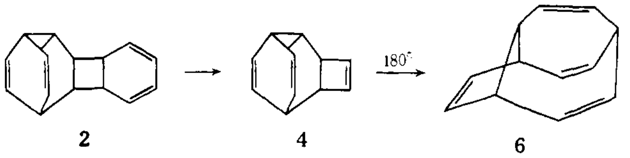


Figure 1. Partial nmr spectra (60 MHz) of **14** (curve A) and **16** (curve B) showing the δ 5.5–6.5 region ($CDCl_3$ solution).

react with 1 mol of dimethylacetylene dicarboxylate to afford adducts which undergo retrograde (4 + 2) cycloaddition into dimethyl phthalate and **3**[3] and **4**,[4] respectively. Also, Schroder has noted that heating of **3** at

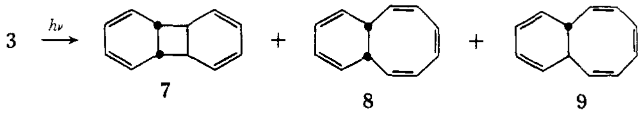


1 3 5



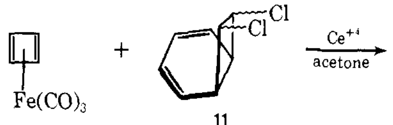
2 4 6

120° for 24 hr results in the formation of equal amounts of hydrocarbon **5** (stereochemistry undetermined) and benzene.[5] The new $(CH)_{12}$ isomer **6** is similarly obtained by pyrolysis of **4** in the gas phase at 480°.[5] Finally, irradiation of **3** in ether solution at −30° for 10 hr has been found to provide low yields of three new $(CH)_{12}$ hydrocarbons (**7–9**).[6]

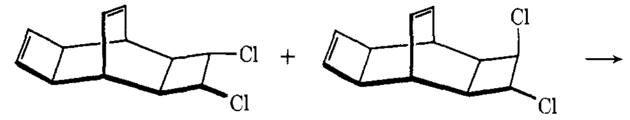


7 8 9

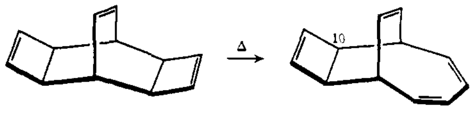
For reasons that will emerge, our initial goal was the unequivocal synthesis of *exo*-tricyclo[4.4.2.0^{7,10}]dodecatetraene (**15**), the exo isomer of **5**. To this end, oxidation of cyclobutadieneiron tricarbonyl (**10**) with ceric ammonium nitrate in the presence of a cis,trans mixture of 7,8-dichlorobicyclo[4.2.0]octadiene (**11**) at 5° in acetone solution was found to give the Diels–Alder adducts **12** and **13** in a combined yield of 52%. Column chromatography of the product mixture on neutral alumina served to separate cis dichloride **12**, mp 131–132°, from the trans isomer **13**, mp 94–95°. The cis and trans relationships of the chlorine substituents in **12** and **13**, respectively, were apparent from the nmr spectra of these substances. Thus, whereas both **12** and **13** display a six-proton multiplet at δ 2.5–3.1 due to the methine protons, a two-proton cyclobutene singlet at 5.87, and a second multiplet in the vinyl region, the absorptions due to the >CHCl protons differ significantly. In the case of **12**, these protons give rise to a narrow ($W_{1/2}$ = 5.5 Hz) multiplet at δ 4.1–4.25 as expected from a molecule possessing such symmetry;[7] in contrast, the >CHCl absorption of **13** consists of two broad overlapping multiplets at δ 4.10–4.72.



10 11



12 13



14 15

The overall stereochemical configurations of **12** and **13** have been assigned in accordance with the established[8] reactivity of bicyclo[4.2.0]octadienes in Diels–Alder reactions and with the energetically favorable secondary orbital interactions expected to be operative in the transition state of the cycloaddition.[9,10] Accordingly, it follows that because the dichlorocyclobutane moiety in **11** sterically inhibits the approach of cyclobutadiene from the top surface, this halogenated ring necessarily becomes cis to the developing ethylene bridge. The exo orientation of the cyclobutene ring was established by dechlorination of **12** and **13** with sodium phenanthrene in tetrahydrofuran solution. The resulting hydrocarbon **14** displays a highly symmetrical nmr spectrum consisting *inter alia* of a single sharp singlet at δ 5.84 arising from the four equivalent cyclobutene protons. The exo,exo stereochemistry of **14** is further substantiated by comparison with the spectrum of **16** (Figure 1).

Pyrolysis of **14** at 500° and 15 mm readily afforded the isomeric $(CH)_{12}$ hydrocarbon **15**. The ultraviolet spectrum of **15** (isooctane) shows maxima at 258 (ϵ 4100), 268 (ϵ 4300), and 278 nm (2500) in good agreement with

---

Tetrahedron Lett., 61 (1970); J. F. M. Oth, J.-M. Gilles, and G. Schröder, *ibid.*, 67 (1970).

(3) G. Schröder and W. Martin, *ibid.*, 78, 117 (1966); *Angew. Chem., Int. Ed. Engl.*, 5, 130 (1966).

(4) G. Schröder, *Chem. Ber.*, 97, 3131 (1964).

(5) J. N. Labows, Jr., J. Meinwald, H. Röttele, and G. Schröder, *J. Amer. Chem. Soc.*, 89, 612 (1967).

(6) G. Schröder, W. Martin, and H. Röttele, *Angew. Chem.*, 81, 33 (1969); *Angew. Chem., Int. Ed. Engl.*, 8, 69 (1969); H. Rottele, W. Martin, J. F. M. Oth, and G. Schröder, *Chem. Ber.*, 102, 3985 (1969).

(7) Compare the cis-exo adduct of benzyne and *cis*-3,4-dichlorocyclobutene: R. N. McDonald and D. G. Frickey, *J. Amer. Chem. Soc.*, 90, 5315 (1968).

(8) For a review, see G. Schröder, "Cyclooctatetraen," Verlag Chemie, Weinheim, Germany, 1965.

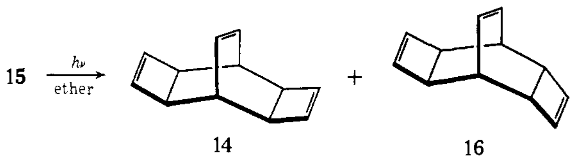
(9) R. Hoffmann and R. B. Woodward, *J. Amer. Chem. Soc.*, 87, 4388 (1965).

(10) Such secondary orbital effects are recognized to be particularly influential when cyclobutadiene functions as either the diene[11] or dienophile component[12] in (4 + 2) cycloadditions.

(11) (a) L. Watts, J. D. Fitzpatrick, and R. Pettit, *J. Amer. Chem. Soc.*, 88, 623 (1966); (b) L. A. Paquette and L. D. Wise, *ibid.*, 89, 6659 (1967); (c) L. A. Paquette and J. A. Schwartz, *ibid.*, 92, 3215 (1970).

(12) L. A. Paquette and L. M. Leichter, *ibid.*, 92, 1765 (1970); 93, 4922 (1971).

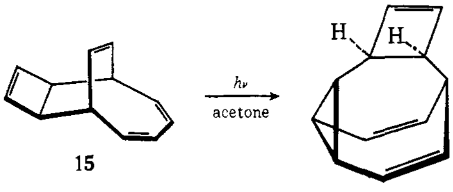
the data reported for **5**.[3] Close correspondence of the nmr spectra was also seen. In **15**, the orientation of the cyclobutene ring must be exo, barring unanticipated rupture and re-formation of the C_7–C_{10} bond with concurrent inversion to the endo configuration. The latter is not the case and experimental verification of the exo assignment to **15** was sought in its direct photoisomerization (1% ether solution, 3 hr, 30°). Under these conditions, the tetracyclic $(CH)_{12}$ isomers **14** and **16** were formed in equal amounts (nmr analysis).[13]



14 **16**

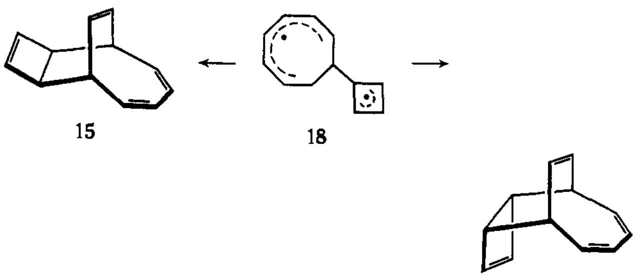
Chromatography of this mixture on silica gel impregnated with silver nitrate resulted in a remarkably clean and simple separation. Whereas elution with ether gave uniquely **16**, elution with methanol–water was needed to recover **14** which was eluted as its silver nitrate complex. The nmr spectrum of **16** clearly reveals the presence of exo and endo cyclobutene rings (Figure 1).[14] Since the formation of **14** from **17** is deemed highly unlikely, the exo stereochemistry of **15** is considered secure.

It is instructive that **14** and **16** are produced in statistical fashion from the photoexcited state of **15**. This can be construed to mean that steric factors are very closely balanced in their influence on the two disrotatory motions in the electronically excited hydrocarbon. The formation of **14** and **16** clearly proceeds from the excited singlet manifold of **15**, since irradiation of **15** under triplet conditions (acetone, E_T = ~82 kcal/mol) afforded only **4**.



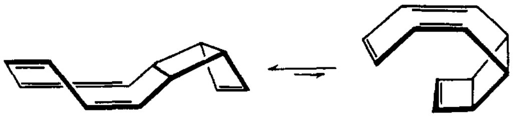
15 **4**

At this point, the thermolysis of **3** was reinvestigated. In our hands, a single $(CH)_{12}$ hydrocarbon was produced. Significantly, this substance was identical in all respects with authentic *exo*-tricyclo[4.4.2.0^{7,10}]dodecatetraene (**15**). The thermal rearrangement of **3** is therefore highly stereoselective. Three mechanisms appear worthy of consideration. First, bond reorganization could be occurring in nonconcerted fashion *via* diradical **18**. In this eventuality, the subsequent recyclization of **18** would be required to be stereochemically unidirectional.



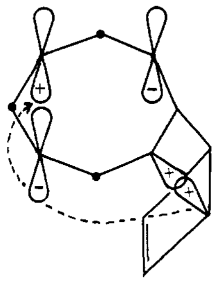
15 **18** **17**

Secondly, the thermal conversion of **3** to **15** could involve the suprafacial [1,5] migration of C_1 from C_2 to C_6. While the preferred conformation of **3** can be considered to resemble closely the tub structure **19a**,



19a **19b**

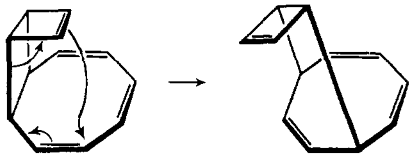
this arrangement does not lend itself geometrically to such a concerted bond shift. Also, although alternative tub conformation **19b** would not suffer from such a stereochemical disadvantage, the nonbonded interactions present in **19b** suggest *a priori* that this structural arrangement might be energetically inaccessible. In actuality, the transition state for this sigmatropic change does not necessarily need to be as severely constrained as **19b**; rather, the unfavorable repulsive interactions present in **19b** may be balanced against the internal angle strain that develops as the cyclooctatriene ring attains planarity as in **20**. In this conformation,



20

which is in fact intermediate between **19a** and **19b**, the pentadienyl system required for the 1,5-suprafacial bonding is capable of best maintaining the approximate coplanarity necessary for application of the orbital symmetry rules.[17]

Alternatively, the stereochemical outcome could be accommodated by a Cope rearrangement as illustrated in **21**. Obviously, a boat-type transition state is like-



21 **15**

wise demanded for this [3,3] sigmatropic change. The process finds analogy with the established mechanism

---

[13] G. Schröder and W. Martin have apparently also observed this photorearrangement [unpublished results mentioned in G. Schröder and J. F. M. Oth, *Angew. Chem., Int. Ed. Engl.*, 6, 414 (1967)]; however, neither stereochemical assignments nor separation of the isomers was made by these workers since the stereochemistry of 15 was unknown to them.

[14] A somewhat similar parallelism is seen in the nmr spectra of *exo*-[15a] and *endo*-tricyclo[4.2.1.0^{2,5}]nona-3,7-dienes[15b] and *exo,exo*-1,6-disubstituted-11,12-diazatetracyclo[4.4.2.0^{2,5}.0^{7,10}]dodeca-3,8,11-trienes.[16]

[15] (a) Netherland Applied Patent 6,503,999; *Chem. Abstr.*, 64, 11103 (1966); (b) L. G. Cannell, *Tetrahedron Lett.*, 6249 (1966).

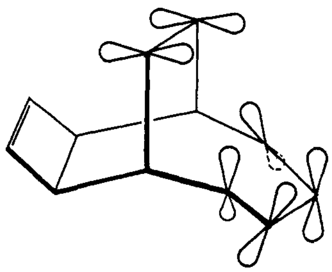
[16] L. A. Paquette and J. F. Kelly, *ibid.*, 4509 (1969); L. A. Paquette and M. R. Short, unpublished results.

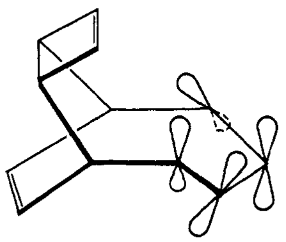
[17] This point has been previously discussed: L. A. Paquette and J. C. Stowell, *Tetrahedron Lett.*, 4159 (1969).

for the skeletal rearrangement of tricyclo$[4.4.0^{1,6}.0^{2,5}]$deca-3,7,9-triene to Nenitzescu's hydrocarbon.[18]

Because of our inability at present either to label **3** properly and specifically with deuterium or to prepare **17** (see below) and establish its stability under the operating conditions, a definitive choice between these mechanisms must await further study.

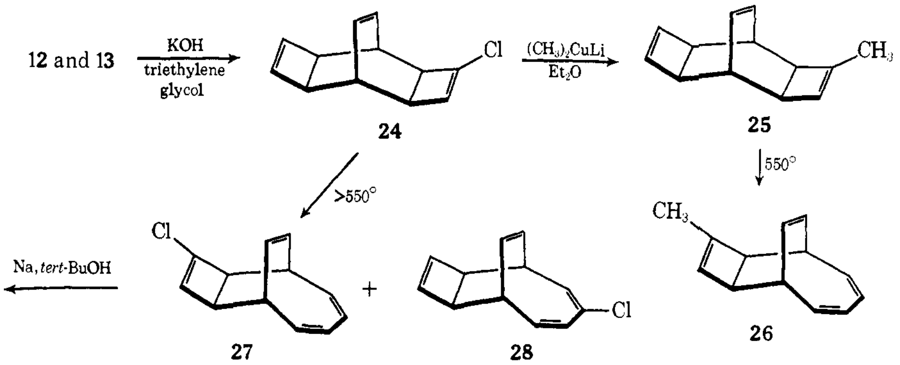
Partial thermolysis of an equimolar mixture of **14** and **16** at 500° revealed that **14** undergoes thermal rearrangement more rapidly than **16**. Thermal rearrangement of pure **16** likewise gave only **15**, suggesting that the endo cyclobutene ring in **16** is cleaved preferentially under these conditions. This rate difference, which has been noted also with *exo*- and *endo*-tricyclo$[4.2.1.0^{2,5}]$nona-3,7-dienes and their dihydro derivatives,[19] may find its origin in the differing amounts of strain relief which come into play in passing from ground state to transition state. The somewhat faster ring opening exhibited by the endo cyclobutene ring can also be understood on the following basis. First, as rehybridization begins, the two newly developing sp^2 orbitals begin to overlap not only with the existing cyclobutene π orbitals but also in orthogonal fashion with the π lobes of the ethylene bridge as in **22**. Alternatively, if cleavage of the bond common to the exo cyclobutene ring were to occur, no overlap of the latter type would be engendered (*cf.* **23**).


22


23

Therefore, the source of the observed preference could be electronic in nature and probably founded in the favorable energetics associated with the developing six-electron (somewhat "aromatic-like"[20]) transition state in **22**. It is of interest to note that the orientation of the π lobes in **22** is reminiscent of the transition state of the Diels–Alder reaction, but with the ethylene system turned 90° out of plane. The preparation of several hydrocarbons which possess a chromophoric system approximated electronically by **22** has recently been described.[21–23]

The above observations raised two meaningful questions. Specifically, if one of the two exo-disposed cyclobutene rings in **14** were monosubstituted, would the requisite disrotatory[24] ring opening be favored or disfavored by the presence of the substituent? To gain evidence on this point, chloride **24** was prepared by dehydrochlorination of dichlorides **12** and **13** with potassium hydroxide in triethyleneglycol at 180–190°.[25]



24 **25** **26** **27** **28** **29**

The reaction of **24** with lithium dimethylcuprate[26] afforded the methyl derivative **25**. Thermal rearrangement of **25** at 550° in the gas phase led exclusively to the 3-methyl isomer **26**, whose structural assignment follows unequivocally from its spectral data (see Experimental Section). None of the isomeric 8-methyl derivative was seen. In the case of **24**, a mixture of **27** and **28** was obtained. At 575°, the ratio of these products was 95:5 (10% recovered **24**), whereas at 500° a 78:22 distribution (39% recovered **24**) resulted. Reduction of **27** with sodium in *tert*-butyl alcohol led to a dihydro product tentatively assigned structure **29**.

On this basis, rupture of the nonsubstituted cyclobutene ring would appear to be kinetically preferred. However, because evidence bearing on the question of thermodynamic stability has not been obtainable, it is entirely plausible to argue that *both* cyclobutene rings in such structures undergo rupture at the elevated temperatures (not necessarily synchronously) to afford the strained pentaene intermediate **30**. Molecular models readily attest to the fact that this molecule is forced to exist in a severely twisted conformation closely approximating **31**.[27] Some measure of strain relief is

---

(18) H. H. Westberg, E. N. Cain, and S. Masamune, *J. Amer. Chem. Soc.*, 91, 7512 (1969).

(19) H. M. Frey, J. Metcalfe, and J. M. Brown, *J. Chem. Soc. B*, 1586 (1970).

(20) M. J. S. Dewar, "The Molecular Orbital Theory of Organic Chemistry," McGraw-Hill, New York, N. Y., 1969, p 335 ff.

(21) L. A. Paquette and J. C. Philips, *Chem. Commun.*, 680 (1969).

(22) L. A. Paquette and J. C. Philips, *J. Amer. Chem. Soc.*, 91, 3973 (1969).

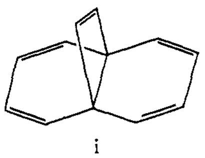
(23) L. A. Paquette, J. C. Philips, and R. E. Wingard, *ibid.*, **93**, 4516 (1971).

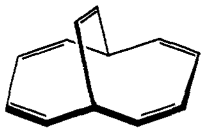
(24) Too many factors militate against the operation of a concerted conrotatory cleavage initially to a cis,trans diene in these molecules. Chief among them is the excessive degree of strain expected at the transition state.

(25) The method of W. Metzner and W. Hartmann, *Chem. Ber.*, 101, 4099 (1968).

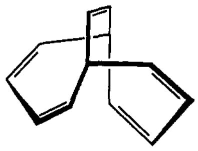
(26) E. J. Corey and G. H. Posner, *J. Amer. Chem. Soc.*, **89**, 3911 (1967); **90**, 5615 (1968).

(27) It is worthy of note that the introduction of a central bond into **30** as in the known pentaene i[22,23] exerts a dramatic alteration in the overall molecular conformation.


i



30



31

available to **30** by means of a thermally induced diene-to-cyclobutene cyclization.[28] For steric reasons, the developing cyclobutene ring would necessarily adopt an exo orientation. Additionally, in the monosubstituted derivatives, maximum strain relief would likely be achieved by formation of the substituted cyclobutene ring which would effect removal of the attached group from the area of most severe steric compression. This hypothetical mechanism, although grossly reasonable, must await the independent synthesis of **30**.

Finally, turning again to the synthetic aspects of this study, one can conceive an entirely plausible one-step synthesis of **14** *via* the cycloaddition of cyclobutadiene to cylooctatetraene. We have studied this reaction but have found, however, that only trace amounts of products are formed. Apparently, the concentration of bicyclo[4.2.0]octatriene, the valence tautomer of cyclooctatetraene required for cycloaddition, is present at a concentration level too low[29] for reasonably rapid second-order reaction; as a result, the polymerization of cyclobutadiene is the predominant reaction.

Experimental Section[30]

Addition of Cyclobutadiene to 7,8-Dichlorobicyclo[4.2.0]octadiene. Ceric ammonium nitrate (22.8 g, 20.8 mmol) was added during 30 min to a solution of *cis*- and *trans*-7,8-dichlorobicyclo[4.2.0]octa-2,4-diene (1.82 g, 10.4 mmol)[31] and cyclobutadiene-iron tricarbonyl (2.00 g, 10.4 mmol)[11b] in 200 ml of acetone at 5° with stirring. The ice bath was removed and stirring was continued for 30 min more. The solution was poured into 400 ml of saturated salt solution and extracted with ether. The combined organic layers were dried, evaporated, and chromatographed on alumina (elution with pentane). The resulting solid was recrystallized from ethanol to give 1.22 g (52%) of white crystals, mp 75–125°.

A 200-mg sample of this solid was rechromatographed on alumina. Elution with pentane gave the pure trans isomer **13**: mp 94–95°; $\delta_{\mathrm{TMS}}^{\mathrm{CDCl_3}}$ 2.5–3.1 (m, 6 H, methine), 4.1–4.7 (m, 2 H, >C*H*Cl), 5.87 (s, 2 H, cyclobutene), and 5.9–6.4 (m, 2 H, olefinic). *Anal.* Calcd for $C_{12}H_{12}Cl_2$: C, 63.45; H, 5.33. Found: C, 63.43; H, 5.29.

Elution with ether gave the pure cis isomer **12** which was recrystallized from ethanol: mp 131–132°; $\delta_{\mathrm{TMS}}^{\mathrm{CDCl_3}}$ 2.5–3.0 (m, 6 H, methine), 4.1–4.25 (m, 2 H, >C*H*Cl), 5.87 (s, 2 H, cyclobutene), and 6.05—6.25 (broad t, 2 H, olefinic). *Anal.* Calcd for $C_{12}H_{12}Cl_2$: C, 63.45; H, 5.33. Found: C, 63.43; H, 5.27.

***exo,exo*-Tetracyclo[4.4.2.0^{2,5}0^{7,10}]dodecatriene (14).** Sodium phenanthrene was prepared by adding 310 mg (0.014 g-atom) of sodium to a solution of 2.67 g (0.015 mol) of phenanthrene in 30 ml of dry tetrahydrofuran. The dark green solution was stirred for 18 hr at room temperature.

Sodium phenanthrene (4 ml of the above solution) was added to 227 mg (1.00 mmol) of a mixture of **12** and **13**. The first portion was rapidly decolorized, but the green color persisted at the end of the addition. After 10 min, one drop of water was added to decolorize the solution. The solvent was evaporated and the residue was distilled at 50° (10 mm) to give 108 mg (69%) of **14** which contained a trace of phenanthrene. An analytical sample purified by preparative vpc had mp 25.5–26.5°: $\delta_{\mathrm{TMS}}^{\mathrm{CDCl_3}}$ 2.5 (m, 2 H, methine), 2.72 (s, 4 H, cyclobutene methine), 5.8 (m, 4 H, olefinic), and 5.84 (s, 4 H, cyclobutene); $\nu_{\max}^{\text{neat}}$ 780 cm^{-1}. *Anal.* Calcd for $C_{12}H_{12}$: C, 92.25; H, 7.75. Found: C, 92.54; H, 7.67.

***exo*-Tricyclo[4.4.2.0^{7,10}]dodecatetraene (15). A. Pyrolysis of 14.** A 100-mg sample of **14** was passed through a glass bead packed quartz tube heated to 500° at 10 mm with a slow stream of nitrogen. There was obtained 71 mg of pale yellow liquid which consisted of **14** (40%) and **15** (60%). The two components were collected by preparative vpc. The nmr spectrum of the recovered tetracyclic compound showed that it was indeed pure **14**. The isolated sample of **15** was identical in all respects with the material prepared in B.

B. Heating of *cis,syn,cis*-Tricyclo[8.2.0.0^{2,9}]dodeca-3,5,7,11-tetraene (3).[3] A 94-mg sample of **3**[3] was heated in an evacuated sealed tube at 120° for 12 hr. The product was purified by preparative vpc to give 33 mg of pure **15**.

Irradiation of 15 in Ether. A solution of 1.30 g of **15** in 450 ml of anhydrous ether was irradiated with a 450-W mercury arc through quartz for 1 hr. The ether was carefully removed by distillation through a Vigreux column, and the residual oil was chromatographed on a column of silver nitrate–silica gel.[32] Elution with ether gave **16** which was further purified by preparative vpc: 206 mg; $\delta_{\mathrm{TMS}}^{\mathrm{CDCl_3}}$ 2.72 (broad s, 4 H), 3.06 (m, 2 H), 5.62 (s, 2 H, cyclobutene), 6.03 (m, 2 H, olefinic), and 6.27 (s, 2 H, cyclobutene); $\nu_{\max}^{\text{neat}}$ 760 cm^{-1}. *Anal.* Calcd for $C_{12}H_{12}$: C, 92.25; H, 7.75. Found: C, 92.03; H, 7.93.

Elution with methanol–water gave the silver nitrate complex of **14**. The methanol was evaporated and the water solution was treated with excess ammonium hydroxide. Pentane extraction followed by vpc purification of the extract gave 107 mg of pure **14**.

In a separate experiment, a solution of 0.500 g of **15** in 25 ml of ether was irradiated in quartz with a less intense light source for 4 hr. Molecular distillation gave 0.378 g (76%) of equal amounts (nmr integration) of **16** and **14**.

Irradiation of 15 in Acetone. A solution of 40 mg of **15** in 4 ml of acetone was irradiated as above through a Pyrex filter. After 17 hr, vpc analysis gave evidence of 85 parts of **4**, 5 parts of **15**, and 10 parts of a mixture of **14** and **16**. Much of the product was polymer. Preparative vpc collection gave 8 mg of **4**, the nmr and infrared spectra of which are identical with those published by Schröder.[4,33]

Partial Thermal Rearrangement of a Mixture of 14 and 16. A 100-mg sample of an equimolar mixture of **14** and **16** was pyrolyzed at 500° in the above manner. There was obtained 98 mg of pale yellow liquid, vpc analysis of which indicated the presence of 40% unchanged starting material and 60% **15**. These were collected by preparative vpc. Nmr analysis revealed that the ratio of **14**:**16** was somewhat less than 1.0. The same method of analysis showed that the isolated sample of **15** was uncontaminated with **17**.

Thermal Rearrangement of 16. A 124-mg sample of **16** was subjected to the pyrolysis procedure described above (500°, 10 mm) to give 120 mg of pale yellow oil. Vpc analysis showed only two components: **16** (56%) and **15** (44%). These components were isolated by preparative vpc to give 52 mg of pure **16** and 36 mg of pure **15**.

***exo,exo*-3-Chlorotetracyclo[4.4.2.0^{2,5}.0^{7,10}]dodecatriene (24).** Potassium hydroxide (2.20 g of 85%, 33.3 mmol) and 10 ml of triethylene glycol were heated to 185° in a test tube. The mixture of **12** and **13** (2.53 g, 11.1 mmol) was added cautiously over 15 min, and heating was continued for an additional 15 min at 180–190°. After cooling, the solution was poured into water and extracted with methylene chloride. Evaporation and molecular distillation (100–120° (15 mm)) of the dried extract gave 2.00 g (94%) of **24** as a colorless liquid; $\delta_{\mathrm{TMS}}^{\mathrm{CDCl_3}}$ 2.4–3.1 (m, 6, methines) and 5.73–6.0 (m, 5, olefinic). An analytical sample was obtained by preparative vpc. *Anal.* Calcd for $C_{12}H_{11}Cl$: C, 75.59; H, 5.82. Found: C, 75.79; H, 5.92.

***exo,exo*-3-Methyltetracyclo[4.4.2.0^{2,5}.0^{7,10}]dodecatriene (25).** Cuprous iodide (9.53 g, 50 mmol) and 50 ml of dry ether were cooled under nitrogen in an ice bath. An ether solution of methyllithium

---

(28) For a leading reference which considers the influence of steric constraints in facilitating the ring closure of 1,3-dienes to cyclobutenes, consult G. A. Doorakian, H. H. Freedman, R. F. Ryan, and H. P. Weber, *J. Amer. Chem. Soc.*, 92, 399 (1970).

(29) The concentration of the bicyclic tautomer is known to be only 0.01% at 100°: R. Huisgen, F. Mietzsch, G. Boche, and H. Seidl, *Chem. Soc., Spec. Publ.*, No. 19, 3 (1965).

(30) All melting points are corrected. The nmr spectra were recorded with a Varian A-60A spectrometer and the ultraviolet spectra were determined with a Cary Model 14 spectrophotometer.

(31) R. Huisgen, G. Boche, W. Hechtl, and H. Huber, *Angew. Chem.*, 78, 595 (1966); *Angew. Chem., Int. Ed. Engl.*, 5, 585 (1966).

(32) Prepared by drying a mixture of 20 g of silica gel and 60 ml of 10% aqueous silver nitrate in a rotary evaporator at approximately 70°.

(33) R. Merenyi, J. F. M. Oth, and G. Schröder, *Chem. Ber.*, 97, 3150 (1964).

(62.5 ml, 100 mmol) was added with stirring (glass-covered magnetic bar). After 5 min the mixture was black, chloride **24** (1.91 g, 10.0 mmol) was added, and stirring was continued for 24 hr at room temperature. Water was added dropwise until gas evolution ceased and then 50 ml of water was introduced. The ether layer was separated, and the water layer was extracted with ether. The ether was distilled through a Vigreux column, and the residual oil was molecularly distilled to give 1.11 g of a mixture of **24**, **25**, and **14**. These were separated by chromatography on silica gel–silver nitrate (elution with ether) to furnish 660 mg of **25**: $\delta_{\text{TMS}}^{\text{CDCl}_3}$ 1.54 (br s, 3, methyl), 2.3–2.8 (m, 6, methines), 5.57 (m, 1, olefinic proton on substituted cyclobutene ring), 5.65–5.84 (m, 2, olefinic), and 5.87 (s, 2, cyclobutene). *Anal.* Calcd for $C_{13}H_{14}$: C, 91.71; H, 8.29. Found: C, 91.88; H, 8.29.

***exo*-3-Methyltricyclo[4.4.2.0^{2,5}]dodecatetraene (26).** A 200-mg sample of **25** was passed through a quartz tube packed with quartz chips at 10 mm and 550° with a slow stream of nitrogen. Gas chromatography of the pyrolysate (collected at −70°) showed low boilers, a small amount of starting material, one large product peak, and trace amounts of several other materials. The product was purified by preparative scale vpc (58 mg): $\delta_{\text{TMS}}^{\text{CDCl}_3}$ 1.54 (br s, 3, methyl), 2.5–2.9 (m, 2, methine), 3.10 (br s, 2, methine), and 5.5–6.2 (m, 7, olefinic). *Anal.* Calcd for $C_{13}H_{14}$: C, 91.71; H, 8.29. Found: C, 91.54; H, 8.30.

Pyrolysis of 24. A 380-mg sample of **24** was pyrolyzed as above at 575° and 2 mm. Vpc analysis (SF-96 column at 140°) of the condensate signaled the presence of **24** (10%), **27** (86%), and **28** (4%). Preparative scale vpc gave 120 mg of **27**: $\delta_{\text{TMS}}^{\text{CDCl}_3}$ 2.80 (m, 2, methine), 3.15 (m, 1, methine), 3.33 (m, 1, methine), and 5.5–6.3 (m, 7, olefinic). *Anal.* Calcd for $C_{12}H_{11}Cl$: C, 75.59; H, 5.82. Found: C, 75.81; H, 5.62.

Chloride **28** was similarly isolated (16 mg); $\delta_{\text{TMS}}^{\text{CDCl}_3}$ 2.7 (m, 2, methine), 3.35 (br s, 2, methine), 5.65 (m), 6.85 (br s), 5.96, 6.16, and 6.32 (total olefinic, 7 H).

Another thermal rearrangement at 500° and 15 mm gave low boilers and the same three substances in a ratio of 39 : 48 : 12.

Reduction of 27.[34] A mixture of 90.9 mg (0.476 mmol) of **27**, 1 ml of *tert*-butyl alcohol, and *ca.* 200 mg (∼9 mg-atoms) of sodium was added to 2 ml of anhydrous tetrahydrofuran and refluxed under nitrogen for 4 hr. After cooling, the excess sodium was removed and 10 ml of water was added. After extraction with pentane and methylene chloride, the combined organic layers were dried and evaporated to yield a pale yellow oil which was purified by preparative vpc (SF-96, 6 ft, 140°). There was obtained 15.5 mg of **29**: $\delta_{\text{TMS}}^{\text{CDCl}_3}$ 2.47 (br s, 6, methylenes and methines), 2.90 (m, 2, methines), 5.22 (t, 2, cyclobutene), and 5.80 (m, 4, olefinic). *Anal.* Calcd for $C_{12}H_{14}$: C, 91.08; H, 8.92. Found: C, 91.12; H, 8.99.

Acknowledgment. We wish to thank Badische Anilin und Soda Fabrik for a generous gift of the cyclooctatetraene required for this research endeavor.

---

[34] The authors thank M. J. Kukla for his assistance in performing this experiment.

The Stereocontrolled Total Synthesis of *dl*-Gibberellin A_{15}

Wataru Nagata,* Toshio Wakabayashi, Masayuki Narisada, Yoshio Hayase, and Susumu Kamata (in Part)

Contribution from the Shionogi Research Laboratory, Shionogi & Company, Ltd., Fukushima-ku, Osaka, Japan. *Received February 1, 1971*

Abstract: The first total synthesis of *dl*-gibberellin A_{15} (**1**) is described. The tetracyclic α,β-unsaturated ketone **6**, a key intermediate in our previous total synthesis of diterpene alkaloids, was transformed by B ring contraction to the B-nor tetracyclic intermediate **40a**, lacking only the D ring of the gibbane skeleton. This intermediate was converted into the α,β-unsaturated ketone **54**, to which hydrocyanation was successfully applied giving the *cis*-9aβ-cyano 7-ketone (**55**) stereoselectively. The stereochemistry of **55** was determined by dipole moment measurement. Two-carbon chain lengthening of the 9aβ-formyl derivative **60b** derived readily from **55** gave **61a**, which, after tosylation of the 7α-hydroxyl and diacetoxylation of the formyl group, was ozonized selectively giving the 10β-formyl derivative **66**. This intermediate was subjected to a new cyclization method devised for the present purpose giving the hexacyclic intermediate **69** as a mixture of four possible stereoisomers, which, by a three-step sequence, was transformed, with loss of unnecessary asymmetries at C_8, C_9, and C_{13}, into the pentacyclic carboxylic acid **73a** having the complete A–B–C–D structure of gibberellin A_{15}. The intermediate **73a** was finally transformed to *dl*-gibberellin A_{15} by seven-step conversion. The synthesis is perfectly stereocontrolled, and also regioselective except for the final δ-lactone formation step. As expected, the synthetic *dl*-gibberellin A_{15} shows half of the activity of the natural material on rice (Tanginbozu) seedling bioassay.

The discovery[1a] in 1938 of an important class of plant hormones, gibberellins, in the metabolites of *Gibberella fujikuroi*, led to a great deal of interest in the study of the isolation, separation, and structural elucidation of each component,[1b] culminating in the X-ray crystallographical determination[2] of the structure of gibberellic acid, a representative of this class. Since then, interest has been directed toward synthetic and biogenetic studies, and many ingenious approaches to construct gibberellin molecules have been reported in the past decade.[3] Very recently, Mori, *et al.*,[4] by connecting their totally synthetic intermediate with

---

[1] (a) T. Yabuta and Y. Sumiki, *Nippon Nogei Kagaku Kaishi*, **14**, 1526 (1938). (b) For a review, see J. R. Hanson, "The Tetracyclic Diterpenes," Pergamon Press, Oxford, 1968, p 41.

[2] F. McCapra, A. I. Scott, G. A. Sim, and D. W. Yong, *Proc. Chem. Soc.*, 185 (1962).

[3] (a) H. J. E. Loewenthal and S. K. Malhotra, *ibid.*, 230 (1962); *J. Chem. Soc.*, 990 (1965); (b) Y. Kos and H. J. E. Loewenthal, *ibid.*, 605 (1963); (c) G. Stork, S. Malhotra, H. Tompson, and M. Uchibayashi, *J. Amer. Chem. Soc.*, **87**, 1148 (1965); (d) L. J. Dolby and R. J. Milligan, *ibid.*, **88**, 4536 (1966); (e) A. Tahara and O. Hoshino, *Tetrahedron Lett.*, 5031 (1966); (f) R. A. Bell, R. E. Ireland, and L. N. Mander, *J. Org. Chem.*, **31**, 2536 (1966); (g) H. J. E. Loewenthal and H. Rosenthal, *Tetrahedron Lett.*, 3693 (1968); (h) U. R. Ghatak, J. Chakravarty, and A. K. Banerjee, *Tetrahedron*, **24**, 1577 (1968); (i) H. O. House, J. F. Sauter, W. G. Kenyon, and J. J. Riehl, *J. Org. Chem.*, **33**, 957 (1968); (j) Y. Kitahara, T. Kato, M. Funamizu, N. Ototani, A. Inoue, and H. Izumi, *Chem. Commun.*, 1632 (1968); (k) D. J. Beames and L. N. Mander, *ibid.*, 498 (1969); (l) S. K. Dasgupta, S. R. Ghosh, and U. R. Ghatak, *ibid.*, 1253 (1969); (m) E. E. Ziegler and M. E. Condon, *Tetrahedron Lett.*, 2315 (1969); (n) T. Hori and K. Nakanishi, *Chem. Commun.*, 528 (1969); (o) A. A. Shchegolev and V. F. Kucherov, *Bull.*