of **38** with 84 mg of **1** was carried out following the general procedure described previously for the preparation of **9**. The product, after recrystallization from a benzene–ethyl acetate mixture, gave 85 mg (65%) of white crystals: mp 219–220 °C; NMR (τ 2.63 (1 H, t, J = 8 Hz, PyH), 2.94 (1 H, d, J = 8 Hz, PyH), 3.06 (1 H, d, J = 8 Hz, PyH), 3.10–3.40 (3 H, m, ArH), 3.42 (1 H, s, ArH), 4.48 (1 H, s, ArH), 5.88 (2 H, AB q, J = 13 Hz, $ArCH_2S$), and 6.18–7.92 (14 H, m, $ArCH_2$, $ArCH_2S$, and $PyCH_2S$); mass spectrum m/e 439, 437; UV (CH_3CN) 280 nm (ϵ 4370) and 268 (8112). Anal. ($C_{25}H_{24}NS_2Cl$) C, H, N.

9²-Chloro-3-pyrida-3-[2,6],6-benza-6-[1,4;2,5],9-benza-9-[1,3]-spiro[5.5]undecaphane-1,4-diene (24).[19] The benzyne–Stevens rearrangement of 148 mg of **39** was carried out following the general procedure described previously for the preparation of **10**. After the product had been purified by chromatography over silica gel, there was isolated 164 mg (81%) of a mixture of isomers having the expected NMR and mass spectral (m/e 515 and 513) properties for the benzyne–Stevens, ring-contracted product. This was directly oxidized with m-chloroperbenzoic acid (85%) in chloroform to give 188 mg of the corresponding bissulfoxide. A solution of this in 50 mL of toluene was boiled under reflux for 18 h. After concentration, the residual solid was chromatographed over silica gel using a 1:1 mixture of dichloromethane and petroleum ether (30–60 °C) for elution, to give 29 mg (39%) of yellow crystals: mp 226–228 °C; NMR τ 3.01 (2 H, AB q, J = 11 Hz, ArCH), 3.31 (2 H, AB q, J = 11 Hz, ArCH), 2.6–3.4 (7 H, m, ArH), 4.56 (1 H, s, ArH), 6.5–7.9 (8 H, m, $ArCH_2$); mass spectrum (high resolution) 369.127 (calcd mol wt for $C_{25}H_{20}NCl$, 369.128); UV (EtOH) 290 nm (ϵ 6550), 260 (18 480), 251 (24 860), and 246 (24 860). Anal. ($C_{25}H_{20}NCl$) C, H, N.

Acknowledgment. We thank the National Science Foundation for their support of this investigation, Mark Tuttle for technical help, and Professor Brian Ramsey for helpful advice and valuable discussions.

References and Notes

(1) (a) University of Oregon; (b) University of Munich.
(2) V. Boekelheide, K. Galuszko, and K. S. Szeto, *J. Am. Chem. Soc.*, **96**, 1578 (1974).
(3) L. H. Weaver and B. W. Mathews, *J. Am. Chem. Soc.*, **96**, 1581 (1974).
(4) T. Otsubo and V. Boekelheide, *Tetrahedron Lett.*, 3881 (1975).
(5) H. Heany, J. M. Jablonsky, and C. T. McCarty, *J. Chem. Soc., Perkin Trans. 1*, 2903 (1972).
(6) I. C. Calder and P. J. Garratt, *J. Chem. Soc. B*, 660 (1967).
(7) R. C. Lord, B. Nolin, and H. D. Stidham, *J. Am. Chem. Soc.*, **77**, 1365 (1955).
(8) J. E. Richman and H. E. Simmons, *Tetrahedron*, **30**, 1769 (1974).
(9) A. R. Katritzky, Ed., "Physical Methods in Heterocyclic Chemistry", Academic Press, New York, 1963, p 67.
(10) R. H. Mitchell, T. Otsubo, and V. Boekelheide, *Tetrahedron Lett.*, 219 (1975).
(11) A. W. Hanson, *Acta Crystallogr., Sect. B*, **33**, 257 (1977).
(12) Estimated from data given by M. Klessinger, *Angew. Chem.*, **84**, 544 (1972); *Angew. Chem., Int. Ed. Engl.*, 11, 525 (1972).
(13) E. Heilbronner, V. Hornung, F. H. Pinkerton, and S. F. Thomas, *Helv. Chim. Acta*, **55**, 289 (1972).
(14) Private communiation from Professor Brian Ramsey.
(15) Elemental and mass spectral analyses were determined by Dr. R. Wielesek, University of Oregon Microanalytical Laboratories. Melting points are uncorrected and were taken with a Mel-Temp apparatus. Infrared spectra were measured with a Beckman IR-7 instrument and visible and ultraviolet spectra with a Cary 15. NMR spectra were measured using deuteriochloroform as solvent with tetramethylsilane as an internal standard, unless otherwise specified, and were obtained with a Varian XL-100. Mass spectra were taken using a Consolidated Model 21-110 spectrometer at 70 eV.
(16) V. Boekelheide and W. J. Linn, *J. Am. Chem. Soc.*, **76**, 1286 (1954).
(17) H. Heany, J. M. Jablonsky, and C. T. McCarty, *J. Chem. Soc., Perkin Trans. 1*, 2903 (1972).
(18) The separation and characterization of the individual isomers are described in the Ph.D. Disseratation of I. D. Reingold, University of Oregon, 1976.
(19) The systematic names given to the triple-layered cyclophanes follow those proposed by H. Lehner (*Monatsh. Chem.*, **107**, 565 (1976)).
(20) R. Gray and V. Boekelheide, *Angew. Chem.*, **87**, 138 (1975); *Angew. Chem., Int. Ed. Engl.*, **14**, 107 (1975).

A Study of the Synthesis and Properties of [2.2.2.2](1,2,4,5)Cyclophane[1]

Richard Gray and V. Boekelheide*

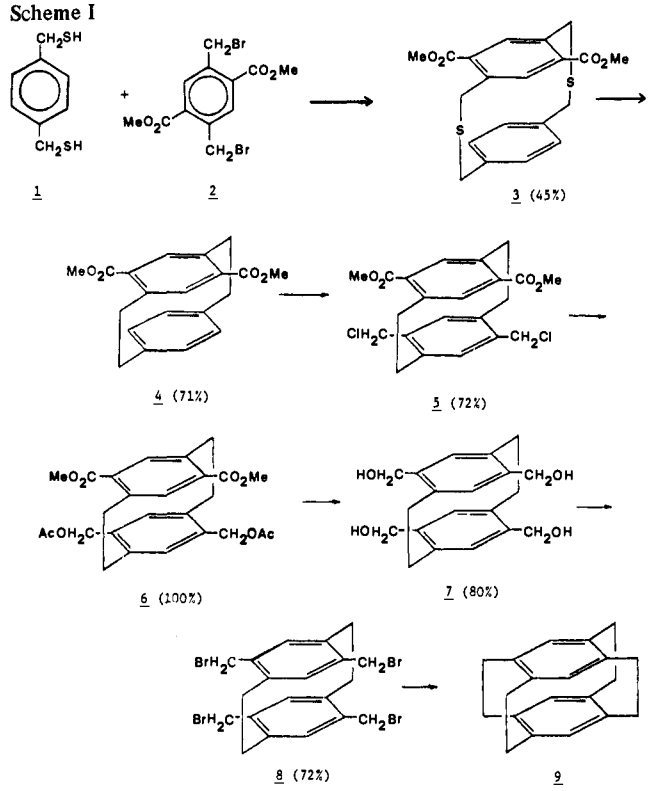
Contribution from the Department of Chemistry, University of Oregon, Eugene, Oregon 97403. *Received September 7, 1978*

Abstract: The synthesis of [2.2.2.2](1,2,4,5)cyclophane (**9**), the first tetra- (two-atom bridged) cyclophane, is reported. The key to its successful synthesis (see Schemes I and II) lay in combining the traditional approach and formation of dithiacyclophane **3** followed by sulfur expulsion to give **4**, with the use of transannular reactions special to [2.2]paracyclophanes: (1) electrophilic substitution of **4** giving exclusively chloromethylation at positions pseudogem to the ester groups, and (2) transannular carbene insertion converting **13** to **9**. Alternatively, **11** was obtained in quantitative yield by a transannular pinacol rearrangement of tetraol **7**. An X-ray crystallographic analysis of **9** shows each of the benzene rings to be in a highly strained boat conformation. This is reflected in the ease with which the benzene rings react with dienophiles such as perfluoro-2-butyne and dicyanoacetylene to give the corresponding mono- and bis(barrelene) adducts, **17–19** and **22**. Addition of singlet oxygen to **9** likewise occurs readily to give the corresponding epidioxide **23** and from this a series of transformation products. The copper-catalyzed thermal addition of ethyl diazoacetate to **9** has been utilized to provide a synthesis of [2.2.2.2](1,2,4,5)-7′-methyltropylioparacyclophane (**37**). Birch reduction of **9** to give **14** followed by addition of dichlorocarbene led to **15**. Lithium metal reduction of **15** then gave the caged hydrocarbon **16**. However, all attempts to effect solvolytic ring opening of **15** to give a cyclophane with a cyclooctatetraene moiety in each deck were unsuccessful. Irradiation of **17**, though, does give a cyclophane containing a cyclooctatetraene moiety.

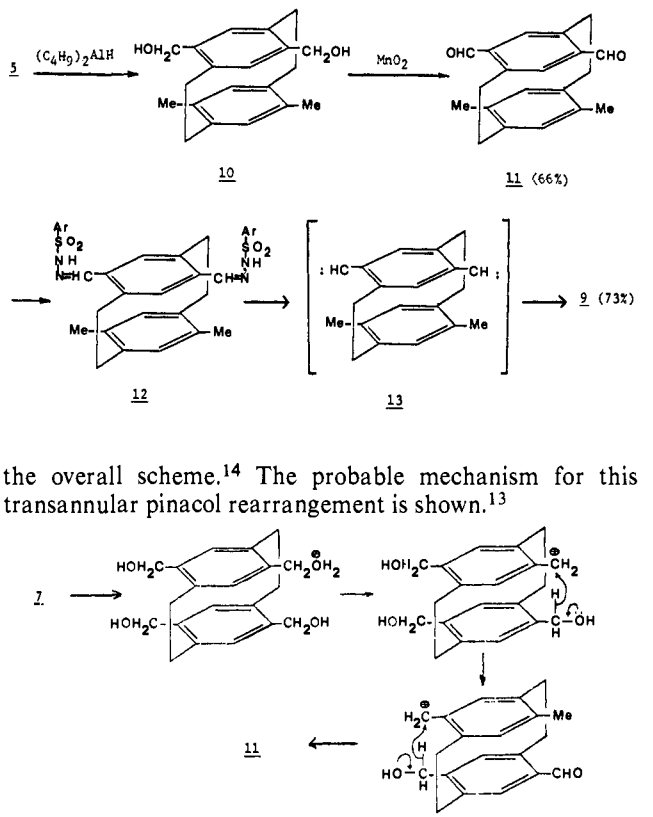
Since the first report on the synthesis and properties of [2.2]paracyclophane,[2] there has been a tremendous interest in the "bent and battered benzene rings of cyclophane chemistry."[3a] Of particular interest are the multibridged cyclophanes in which each of the bridges has two carbon links.[3b] Aside from the [2.2]paracyclophanes and the trivial case of [2.2]orthocyclophanes, the known examples of such multibridged cyclophanes include both syn and anti isomers of the [2.2]metacyclophanes,[4] [2.2]metaparacyclophanes,[5,6] [2.2.2](1,3,5)cyclophanes,[7] [2.2.2](1,2,4)cyclophanes,[8] [2.2.2](1,2,4)(1,3,5)cyclophanes,[9] and [2.2.2](1,2,5)cyclophanes.[9] We became interested in extending the series to examples of tetrabridged cyclophanes and, from an inspection of molecular models, it appeared that of the various possibilities

0002-7863/79/1501-2128$01.00/0

Scheme I



Scheme II



[2.2.2.2](1,2,4,5)cyclophane (**9**) offered an opportunity to explore especially interesting chemistry. The present communication reports our synthesis and a study of the properties of [2.2.2.2](1,2,4,5)cyclophane.[10]

Although our approach to the synthesis of **9** (see Scheme I) utilized standard procedures of dithiacyclophane formation–sulfur extrusion (**1** + **2** → **3** → **4**) developed earlier,[11] it was also designed to take advantage of the unusual chemistry inherent to [2.2]paracyclophanes.[3] Thus, the slow step in electrophilic substitution of [2.2]paracyclophanes is proton loss from the intermediate carbonium ion and, when the opposite deck has a basic group, such as a carbonyl, that can assist in proton removal, electrophilic substitution occurs pseudogeminate to that basic group.[8,12,13] In the event, chloromethylation of **4**, using chloromethyl methyl ether and massive amounts of aluminum chloride, gave exclusively isomer **5** in 74% yield. The subsequent steps from **5** to **9** are those normally employed for forming bridges.

Unfortunately, the tetrabromide **8** is an exceedingly insoluble compound and its conversion to **9** via a heterogenous reaction with phenyllithium proceeded in very poor yield. An alternative approach was, therefore, developed as summarized in Scheme II. Reduction of **5** with diisobutylaluminum hydride in boiling benzene gave the diol **10** which, on direct oxidation with activated manganese dioxide, yielded the dialdehyde **11** in 66% overall yield from **5**. Because of the proximity of the aldehyde and methyl groups in **11**, it was anticipated that conversion of the aldehyde to a carbene would be followed by a transannular carbon–hydrogen insertion reaction to give **9**. For this purpose **11** was converted to the corresponding bis(*p*-toluenesulfonylhydrazone) **12** which, on treatment with base followed by irradiation, gave the desired carbene-insertion reaction, producing **9** in 72% overall yield from **11**.

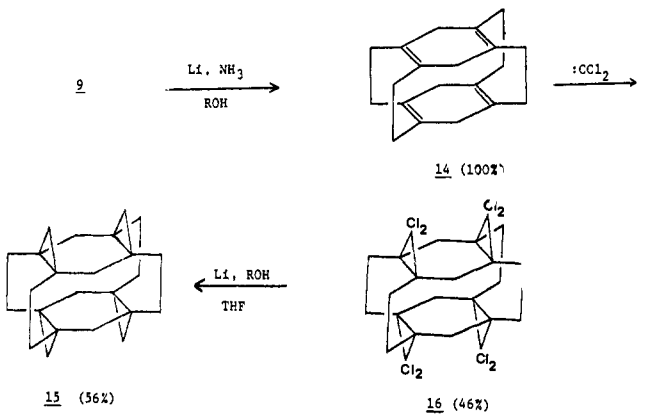
Although the route to [2.2.2.2](1,2,4,5)cyclophane (**9**) in Scheme II has proved to be quite satisfactory and has provided all of the material for our chemical studies, it was later found that the tetraol **7** undergoes an unusual, transannular, pinacol-type rearrangement to give the dialdehyde **11** in quantitative yield, and this probably represents an improvement in the overall scheme.[14] The probable mechanism for this transannular pinacol rearrangement is shown.[13]

9 crystallizes as white plates melting at 350 °C. Its ^{1}H NMR spectrum shows the aromatic protons as a singlet at δ 5.96 and its bridging methylene protons as an AA′BB′ multiplet at δ 2.5–3.5. Its ultraviolet absorption spectrum shows maxima at 248 nm (sh, ϵ 3610), 294 (660), and 303 (1050). The ultraviolet spectrum of **9** is in agreement with what would be predicted for a highly distorted benzene ring,[15] whereas the upfield shift for the signals of the aromatic protons in the ^{1}H NMR spectrum suggests a close proximity of the benzene rings in the two decks, but with boat-shaped benzene rings allowing the bowsprit and stern aromatic protons to be farther apart than in [2.2.2](1,3,5)cyclophane.[16]

An X-ray crystallographic analysis of **9** has been made by Hanson,[17] and the benzene rings are distorted to a boat to almost exactly the same extent as in [2.2]paracyclophane,[18] except that in **9** the benzene boats are inverted to the outside rather than to the inside as in [2.2]paracyclophane.[19] The fact that the distance between the two decks of **9** is only 2.688 Å suggests a high strain energy and this conclusion is supported by the unusually long (1.591 Å) bond length for the sp^3-sp^3 carbon–carbon bonds in the bridges. Lindner has calculated the strain energies and molecular geometries of a number of cyclophanes by the π-SCF-force-field method.[20] His calculated values for the bond lengths in **9** are in surprisingly good agreement with those observed, and provide confidence that the values calculated for other cyclophanes, such as the still unknown [2.2.2.2.2.2](1,2,3,4,5,6)cyclophane, will be equally as good.

The strain energy for **9**, as estimated by Lindner,[20] is in the range of 36–49 kcal/mol. Transformations converting the benzene rings of **9** to boat-shaped, 1,4-cyclohexadiene moieties would be expected to relieve a great deal of strain and so to proceed with extreme ease. The first such reaction to be studied was the Birch reduction which readily gave the tetrahydro derivative **14** in quantitative yield. X-ray crystallographic examination of **14** shows it to have more or less the same molecular geometry as **9**,[17] but the relief of strain is shown by the shortening of the bridging sp^3–sp^3 carbon–carbon bond length from 1.591 to 1.519 Å in **14**.

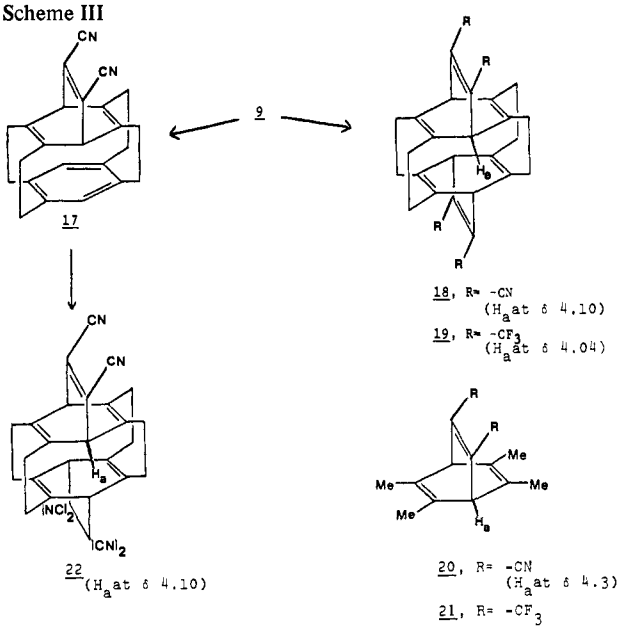
The Birch product **14** appeared to offer interesting possibilities for elaboration, particularly when it was found that the addition of dichlorocarbene, using the phase-transfer technique,[21] readily gave the cage structure **15.** Unfortunately, all attempts to effect solvolytic ring opening of **15,** as a first step toward preparing a cyclophane with cyclooctatetraene decks, were unsuccessful. For characterization, though, reduction of **15** with lithium and *tert*-butyl alcohol in tetrahydrofuran readily gave the white, crystalline hydrocarbon **16.**



Similarly, the benzene rings of **9** readily undergo the Diels–Alder reaction with such dienophiles as dicyanoacetylene and perfluoro-2-butyne. Formation of the monoadduct **17** occurs rapidly and in excellent yield, when **9** is heated with dicyanoacetylene in chloroform. However, on prolonged heating with dicyanoacetylene **9** forms the bis adduct **18** as well. Clearly, an important relief of strain occurs during the addition of the first mole of dicyanoacetylene and only to a lesser extent during the addition of the second mole. Likewise, the addition of perfluoro-2-butyne to **9** smoothly gave the bis adduct **19,** as summarized in Scheme III.

One feature of interest with respect to the bridged, double barrelenes **18** and **19** is that the six ethylene units are favorably oriented in space to undergo a longicyclic interaction. The general principles of longicyclic interactions have been discussed by Goldstein and Hoffman,[22] and in the simple Hückel treatment applied to **18** and **19** one would predict that the longicyclic interaction would lead to a narrowing of the HOMO–LUMO gap but would provide no net stabilization.

Scheme III



Since narrowing of the HOMO–LUMO gap should lead to a shift in the ultraviolet absorption to longer wavelengths, it was of interest to compare the absorption spectra of the double barrelenes **18** and **19** with those of appropriate simple barrelenes. The model compounds chosen were compounds **20** and **21,** derived from durene by addition of dicyanoacetylene[23] and perfluoro-2-butyne,[24] respectively. As illustrated in Scheme III, the bright yellow, double barrelene **18** has absorption maxima at 375 nm (ε 500) and 291 (1000), whereas the simple barrelene model **20** has maxima at 361 nm (ε 250) and 274 (750). Similarly, **19** has absorption maxima at 297 nm (ε 160) and 240 (700) compared with the maxima for **21** at 287 nm (ε 70) and 233 (440). Even though the double barrelenes **18** and **19** show shifts to longer wavelengths compared with the simple barrelene models, as predicted, the effect is quite small.

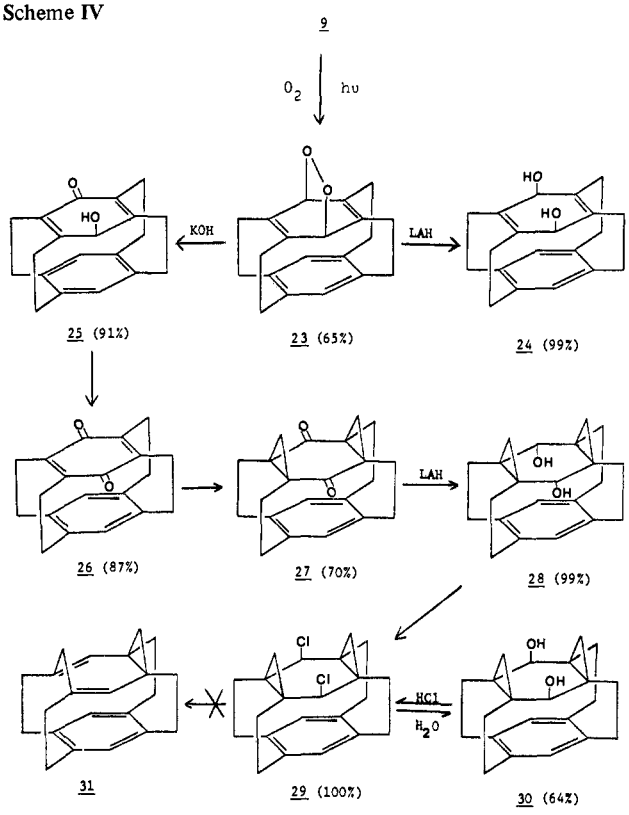
Although the longicyclic interaction in **18** should have no net stabilization and, therefore, no ring current should be present, the bridgehead proton H_a appears at δ 4.1, appreciably upfield compared with the signal for the bridgehead proton H_a in the simple barrelene model. To determine whether, in fact, this upfield shift had any relationship to ring current, the double barrelene **22** was made by the addition of tetracyanoethylene to the monoadduct **17.** In the case of **22** longicyclic conjugation is interrupted by the presence of a saturated bridge and so there can be no ring current. The signal for the bridgehead proton H_a in **22** has exactly the same chemical shift as that in **17.** So the upfield chemical shift for the bridgehead protons of **17** has its origin in some effect other than ring current.

Another Diels–Alder reaction exhibited by [2.2.2.2]-(1,2,4,5)cyclophane is the easy addition of singlet oxygen to give the monoadduct **23.** In this case formation of a bis adduct could not be effected. As summarized in Scheme IV, reduction of the epidioxide **23** with lithium aluminum hydride occurred cleanly to give the diol **24.** However, attempted oxidation of **24** to give the quinone **26** was completely unsuccessful. It was then discovered that treatment of the epidioxide **23** with methanolic potassium hydroxide effected a clean rearrangement to the dienone **25.** Even though **25** is tautomeric with the corresponding aromatic hydroquinone, it showed no tendency to undergo tautomerization. Oxidation of **25** with activated manganese dioxide converted it smoothly in high yield to the quinone **26.**

With the availability of these oxygenated derivatives it became of interest to see whether they could be utilized to allow ring expansion. In particular we wanted to convert the oxygenated ring to a homotropylidene moiety, as in **31,** which might, because of steric interactions, have a very planar π skeleton and so show a very low, or negative, fluxional barrier. For this purpose the diol **24** seemed an ideal starting material. However, the Simmons–Smith cyclopropanation reaction, which usually goes exceptionally well with allylic alcohols,[25] failed with **24,** as did attempts to effect cyclopropanation using diazomethane or dichlorocarbene. Cyclopropanation of the quinone **26** with dimethyloxosulfonium methylide,[26] though, proceeded smoothly, giving **27** in 70% yield. Reduction of **27** with lithium aluminum hydride then gave the endo diol **28,** an acid- and air-sensitive product.

From mechanistic considerations it was anticipated that the exo diol **30** would be required for the ring-opening reaction to form the homotropylidene derivative **31.** Eventually, it was found that this epimeric interconversion could be accomplished by treating **28** with thionyl chloride in pyridine to give **29** and this, in the presence of a trace of moisture, was immediately transformed to the exo diol **30.** The endo diol **28,** having the hydroxyl groups locked between decks, must be highly strained and, once converted to the relatively strain-free exo diol **30,** there is a large energy barrier to reversion to the endo conformation. Thus, the dichloride **29** and the exo diol **30** are

Scheme IV

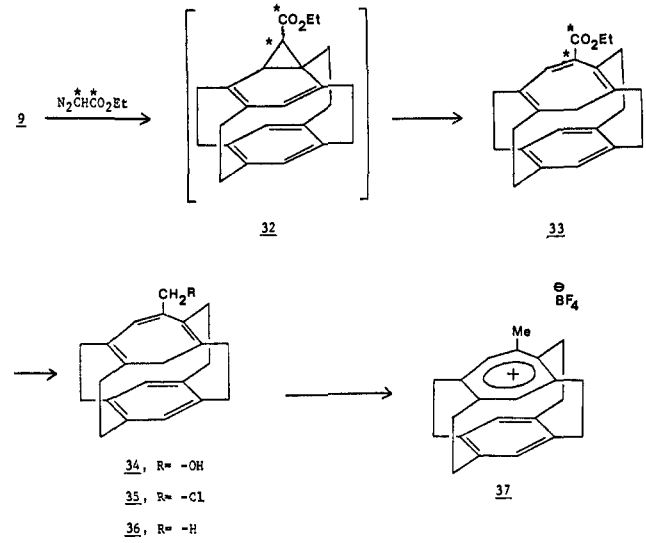


readily interconverted without any trace of formation of endo products. Although the final step, the conversion of **29** to **31** by 1,4-elimination of halogen with ring opening, is well precedented in simple models,[27] all attempts to effect this transformation using various reagents (lithium amalgam, magnesium, phenyllithium, iodide ion, etc.) under a variety of conditions were completely unsuccessful.

Another avenue for benzene ring expansion is the direct addition of carbenes. Treatment of [2.2.2.2](1,2,4,5)cyclophane (**9**) with diazomethane in the presence of cuprous chloride led to a complex mixture of methylenated products, just as has been found for the reaction of diazomethane with [2.2]paracyclophanes.[28-30] Because of our limited supplies of **9**, it was not feasible to separate this mixture and so we turned instead to the copper-catalyzed addition of ethyl diazoacetate to **9**. This proceeded well to give a monoadduct. The ^1H and ^{13}C NMR spectra of the monoadduct did not clearly define whether its structure was that of the norcaradiene **32** or the cycloheptatriene **33**. To settle this question, a synthesis of the monoadduct was made using ethyl diazoacetate enriched with carbon-13 at the carbonyl and α carbons, as shown by asterisks in Scheme V. Spectral analysis of the carbon-13-enriched monoadduct established its structure to be that of the cycloheptatriene **33**. By standard procedures, **33** was then converted to **36**.

Although treatment of **36** with triphenylmethyl fluoroborate appeared to be giving the desired tropylium fluoroborate **37**, the product was very sensitive to moisture, apparently undergoing a rearrangement. In order to obtain good spectral data for **37**, but avoiding the difficulties of isolation, we resorted to the use of a low-molecular-weight polystyrene polymer having triphenylmethyl fluoroborate groups attached along the polymer chain.[31] In this way vacuum-line techniques were used in conducting the hydride abstraction reaction and the insoluble polymeric reagent could either be removed by filtration after its use or simply allowed to remain since its presence does not register in solution spectra. The ^1H NMR spectrum of **37** measured in the presence of the polymer reagent containing triphenylmethyl fluoroborate units is shown in Figure 1.

Scheme V



One of the important questions in observing cyclophanes having one deck with a fully charged ion is the extent of charge-transfer interaction between decks. This is normally deduced from shifts in the electronic and nuclear magnetic spectra. During the course of our studies, [2.2](1,4)tropylioparacyclophane fluoroborate was synthesized independently by the research groups of both Misumi[29] and Keehn.[30] Since the distance between decks in **37** should be appreciably shorter (~2.7 Å) than for [2.2](1,4)tropylioparacyclophane fluoroborate (~3.1 Å), it was expected, and found to be true, that the charge-transfer effect is stronger for **37** than for [2.2]-(1,4)tropylioparacyclophane fluoroborate. In the electronic spectrum of an acetonitrile solution of [2.2](1,4)tropylioparacyclophane fluoroborate the charge-transfer bands appear at 323 nm (ϵ 2230), 353 (1590), and 440 (sh, 524), whereas for solutions of **37** in acetonitrile these bands appear at 351 nm (π ~2000) and 460 (broad maximum, ~440).

The ^1H NMR chemical-shift values for the aromatic protons of **37** are compared with the corresponding protons of [2.2]-(1,4)tropylioparacyclophane fluoroborate in Table I. In each case the deck containing the tropylium ion is skewed somewhat off center from the benzene ring deck. From an examination of molecular models it would appear that, whereas H_a is affected by the off-center skewing, H_b has about the same relative position with respect to the opposite deck as it has in [2.2.2.2](1,2,4,5)cyclophane. The important factors determining the chemical shift value for H_b then are the shielding effect due to the ring current of the opposite deck and the charge-transfer effect which depletes the electron density in the benzene ring. As a rough approximation, the shielding effect due to the ring current in the opposite deck will be about the same for H_b in **37** as for the analogous proton in [2.2.2.2](1,2,4,5)cyclophane (**9**). The difference in the chemical-shift values for H_b in **37** (δ 6.94) and for the analogous proton in **9** (δ 5.96) is 0.98 ppm and this is a reasonable measure of the magnitude of the charge-transfer effect. By a similar analysis, the chemical-shift value of H_b in [2.2]tropylioparacyclophane fluoroborate is δ 7.19, whereas the analogous proton in [2.2]paracyclophanes appears at δ 6.50. This difference, 0.69 ppm, indicates a strong charge-transfer interaction, but a somewhat smaller effect than for **37** where the two decks are closer together.

Although there is no good reference model for the chemical-shift values of the protons on the tropylium ring, it is of interest to compare the H_d protons of **37** and of [2.2]tropylioparacyclophane fluoroborate with those present in tropylium fluoroborate itself, all spectra being determined in the same solvent (CD_3CN). The chemical-shift value for H_d in **37** is δ

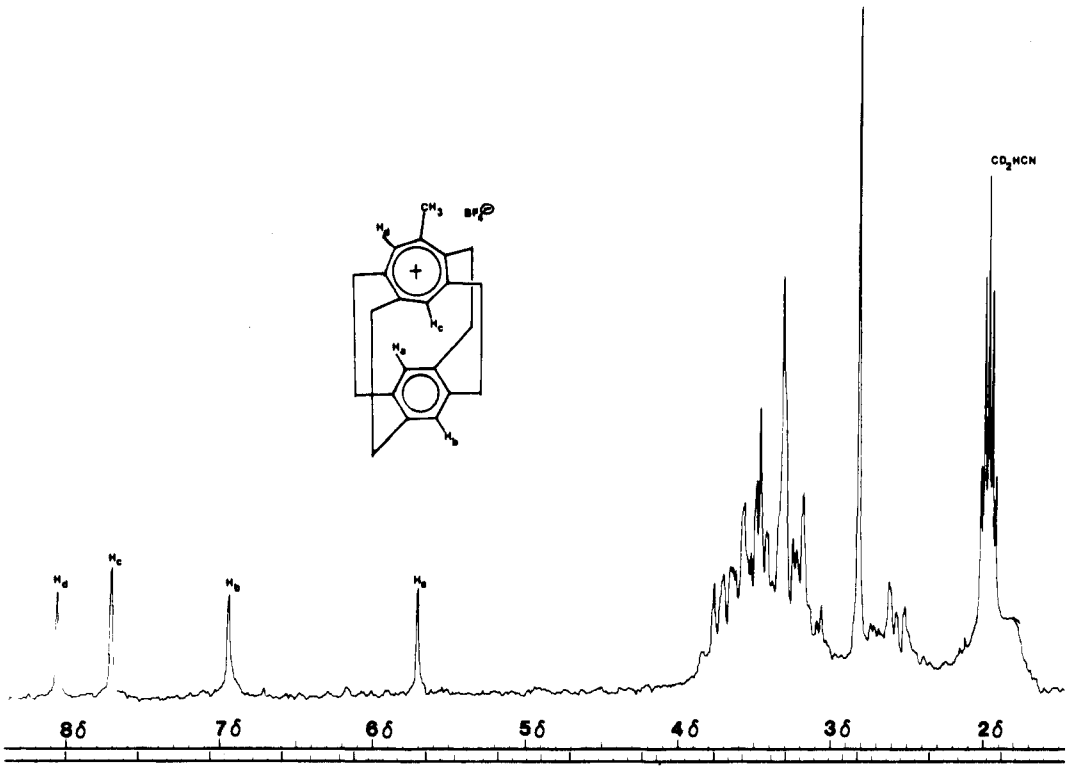
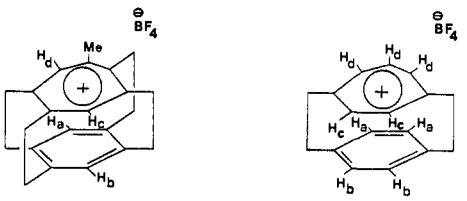


Figure 1. The ^{1}H NMR spectrum of **37** measured in perdeuterioacetonitrile in the presence of the polymer reagent containing triphenylmethyl fluoroborate groups.

Table I. Comparison of the ^{1}H NMR Spectra of [2.2.2.2]-(1,2,4,5)-7′-Methyltropyliocyclophane (**37**) and [2.2]-Tropylioparacyclophane

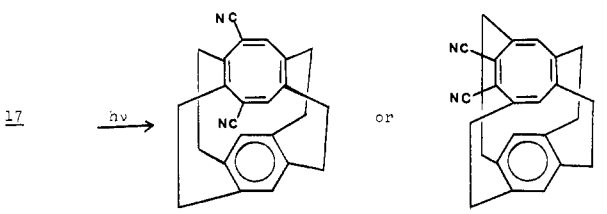


H_a	65.70	66.00
H_b	66.94	7.19
H_c	67.70	67.76
H_d	68.06	68.49

[a] References 29, 30.

8.06, 1.22 ppm upfield from the signal for tropylium fluoroborate (δ 9.28[30]). For [2.2]tropylioparacyclophane fluoroborate, the signal for H_d appears at δ 8.49, a shift upfield of 0.79 ppm. In both cases, the upfield shift of the H_d proton relative to tropylium fluoroborate is the result of the additive contributions of the shielding due to the ring current in the opposite deck and the increased electron density in the tropylium ring due to the charge-transfer effect. The upfield shifts in both cases are strong, but again the magnitude of the shift is greater for **37** than for [2.2]tropylioparacyclophane fluoroborate.

The photochemical conversion of barrelene to cyclooctatetraene has been observed by Zimmerman and his associates.[32] In view of this precedent, the irradiation of the mono- and bisbarrelenes **17–19** was investigated. Irradiation of a solution of **17** in tetrahydrofuran at room temperature with a low-pressure mercury lamp for 2.5 h gave in 41% yield a single yellow crystalline product whose spectral properties are in agreement with its being a cyclophane having a cyclooctatetraene moiety for one deck. From mechanistic considerations the formation of either **38** or **39** would be possible and, although we favor **38** as the correct structure, the electronic and ^{1}H NMR spectral data for the product do not allow a clear decision. The spectral data do suggest that the cyclooctatetraene ring has its normal tub conformation and molecular models indicate that is better accommodated for structure **38** than **39**.



38 **39**

Unfortunately, irradiation of the double barrelenes **18** and **19** gave complex mixtures of products. As yet it has not been possible to isolate from these mixtures the desired cyclophanes with two cyclooctatetraene decks, even though they may possibly be present in trace amounts.

Experimental Section[33]

Dimethyl 2,5-Bis(bromomethyl)terephthalate (2). The dimethyl 2,5-dimethylterephthalate needed for this study was prepared by chloromethylating *p*-xylene,[34] oxidizing the resulting 2,5-bis(chloromethyl)-*p*-xylene with nitric acid to give 2,5-dimethylterephthalic acid,[35] and esterifying this by reaction with thionyl chloride followed by addition of methanol to give in 43% overall yield white crystals, mp 114–116 °C (lit.[36] gives mp 114–116 °C). A solution of 43.2 g of dimethyl 2,5-dimethylterephthalate and 69.5 g of *N*-bromosuccinimide in 500 mL of carbon tetrachloride was heated with a heat lamp until all of the *N*-bromosuccinimide was consumed. After the hot solution had been filtered, the filtrate was cooled, causing the separation of 37.5 g (51%) of crystals. A sample was recrystallized from carbon tetrachloride to give white needles: mp 169–171 °C; IR (KBr) $\nu_{C=O}$ 1720 cm^{-1}; NMR δ 8.06 (2 H, s, ArH), 4.95 (4 H, s, $-CH_2Br$), 3.98

(6 H, s, $-OCH_3$); mass spectrum, *m/e* 378, 380, 382. Anal. ($C_{12}H_{12}Br_2O_4$) C,H.

5,8-Bis(carbomethoxy)-2-11-dithia[3.3]paracyclophane (3). A solution of 60.9 g of **2** and 27.2 g of 1,4-bis(mercaptomethyl)benzene (**1**) in 2 L of degassed dichloromethane was added dropwise with stirring to a flask containing 15 g of potassium hydroxide in 7 L of methanol. When the addition was half-complete, another 15 g of potassium hydroxide was added to the methanol mixture. After the addition was complete, the mixture was acidified, the precipitate was removed by filtration, and the filtrate was concentrated to a volume of ~100 mL. The solid, which separated on standing, was collected and recrystallized from ethyl acetate to give 27.6 g (45%) of white prisms: mp 158.5–159.5 °C; IR (KBr) $\nu_{C=O}$ 1715 cm^{-1}; NMR δ 7.46 (2 H, s, ArH), 6.92 (4 H, AA'BB' m, ArH), 3.94 (6 H, s, $-OCH_3$), 4.17 (4 H, AB, $\Delta\nu$ = 0.98 ppm, J = 14 Hz, $ArCH_2-$), 3.77 (4 H, AB, $\Delta\nu$ = 0.04 ppm, J = 14 Hz, $ArCH_2-$); mass spectrum *m/e* 388. Anal. ($C_{20}H_{20}O_4S_2$) C,H.

3,7-Bis(carbomethoxy)[2.2]paracyclophane (4). A suspension of 7.0 g of **3** in 100 mL of trimethyl phosphite was irradiated at room temperature using a 400-W Hanovia medium-pressure lamp with a Pyrex filter. When the conversion was complete, as analyzed by thin layer chromatography, the clear yellow solution was poured into water with good stirring. After the solution had been stirred a sufficient time for hydrolysis of the trimethyl phosphite, the precipitate was collected by filtration and purified by chromatography over silica gel using toluene as eluant. The main fraction of eluate gave 4.15 g (71%) of white plates: mp 144–145 °C; IR (KBr) $\nu_{C=O}$ 1715 cm^{-1}; NMR δ 7.17 (2 H, s, ArH), 6.50 (4 H, s, ArH), 3.92 (6 H, s, $-OCH_3$), 2.7–4.3 (8 H, m, $ArCH_2-$); mass spectrum *m/e* 324. Anal. ($C_{20}H_{20}O_4$) C,H.

4,7-Bis(carbomethoxy)-12,15-bis(chloromethyl)[2,2]paracyclophane (5). A mixture of 100 g of aluminum chloride in 100 mL of chloromethyl methyl ether was carefully prepared at 0 °C and then allowed to warm to room temperature. To this was added with rapid stirring a solution of 1.0 g of **4** in 15 mL of chloromethyl methyl ether. After the addition was complete, the mixture was stirred for 1 h and then poured into 1 L of crushed ice. To the stirred suspension was added 200 mL of chloroform; the water layer was decanted; and fresh water was added until it remained clear. After the organic layer was separated, it was dried and concentrated. The residual solid was purified by chromatography over silica gel with toluene as eluant to give 935 mg (72%) of white prisms: mp 189–192 °C; IR (KBr) $\nu_{C=O}$ 1712 cm^{-1}; NMR δ 7.24 (2 H, s, ArH), 6.54 (2 H, s, ArH), 3.88 (6 H, s, $-OCH_3$), 4.40 (4 H, AB, $\Delta\nu$ = 0.25 ppm, J = 12 Hz, $-CH_2Cl$), 2.9–4.3 (8 H, m, $ArCH_2$); mass spectrum *m/e* 420, 422, 424. Anal. ($C_{22}H_{22}O_4Cl_2$) C,H.

4,7-Bis(carbomethoxy)-12,15-bis(acetoxymethyl)[2.2]paracyclophane (6). A solution of 1.2 g of **5** in 50 mL of glacial acetic acid containing 2.0 g of silver acetate was heated on a steam bath for 2 h. The resulting suspension was concentrated and then extracted with dichloromethane. After the dichloromethane solution had been washed successively with an aqueous bicarbonate solution and water, it was dried and concentrated to give 1.28 g (96%) of white crystals. A sample, after recrystallization from methanol, yielded white prisms: mp 149–150 °C; IR (KBr) $\nu_{C=O}$ 1715, 1740 cm^{-1}; NMR δ 7.27 (2 H, s, ArH), 6.53 (2 H, s, ArH), 3.93 (6 H, s, $-OCH_3$), 2.00 (6 H, s, CH_3CO), 4.88 (4 H, AB, $\Delta\nu$ = 0.23 ppm, J = 13 Hz), 2.9–4.3 (8 H, m, $ArCH_2-$); mass spectrum *m/e* 468. Anal. ($C_{26}H_{28}O_8$) C,H.

4,7,12,15-Tetrakis(hydroxymethyl)[2.2]paracyclophane (7). A solution of 540 mg of **6** in 20 mL of dry tetrahydrofuran was added dropwise to a boiling solution of 600 mg of lithium aluminum hydride in 75 mL of tetrahydrofuran. The mixture was then boiled under reflux for 48 h before quenching by addition of ethyl acetate followed by water. After the mixture was concentrated, the residue was placed in a Soxhlet and extracted with methanol to give 305 mg (81%) of white crystals, mp 258–263 °C. A sample recrystallized from a water–dimethyl sulfoxide mixture yielded white prisms: mp 264–266 °C; IR (KBr) 3240, 1430, 1190, 1070, 1035, 1000, 900 cm^{-1}; NMR ($(CD_3)_2SO$) δ 6.63 (4 H, s, ArH), 4.69 (4 H, t, –OH), 4.41 (8 H, AB, $\Delta\nu$ = 0.10 ppm, J = 12.5 Hz, $-CH_2O-$), 2.7–3.4 (8 H, AA'BB', $ArCH_2$); UV (EtOH) λ_{max} 230 nm (ϵ 18 200), 290 (330); mass spectrum *m/e* 328. Anal. ($C_{20}H_{24}O_4$) C,H.

4,7,12,15-Tetrakis(bromomethyl)[2.2]paracyclophane (8). A suspension of 158 mg of **7** in 25 mL of benzene was stirred with 2 mL of phosphorus tribromide for 24 h and then 25 mL of water was added and stirring was continued while removing the benzene under reduced pressure. The highly insoluble product was collected by filtration to give 200 mg (72%) of a white powder: mp >250 °C dec.; molecular weight calcd for $C_{20}H_{20}Br_4$ 579.826, found (high resolution mass spectrum) 579.830.

4,7-Bis(hydroxymethyl)-12,15-dimethyl[2.2]paracyclophane (10). To a solution of 670 mg of **5** in 100 mL of boiling benzene was added 10 mL of a 20% solution of diisobutylaluminum hydride in benzene as rapidly as possible while still maintaining a rapid rate of boiling. After the solution had cooled, 300 mL of water was added with stirring and then 200 mL of chloroform followed by enough aqueous hydrochloric acid to clarify the resulting emulsion. The organic layer was washed with water, dried, and concentrated to give 578 mg of a white solid. This was best converted to **11** without further purification. However, recrystallization from chloroform gave a pure sample of **10** as white flakes: mp > 200 °C dec.; NMR δ 6.50 (2 H, s, ArH), 6.15 (2 H, s, ArH), 4.70 (4 H, AB, $\Delta\nu$ = 0.32 ppm, J = 12 Hz, $-CH_2O-$), 2.08 (6 H, s, $-CH_3$), 2.8–3.5 (8 H, m, $ArCH_2-$); mass spectrum *m/e* 296. Anal. ($C_{20}H_{24}O_2$) C,H.

4,7-Bis(formyl)-12,15-dimethyl[2.2]paracyclophane (11). A solution of 578 mg of crude **10** in 100 mL of chloroform containing 3.0 g of activated manganese dioxide[37] was boiled under reflux until analysis by thin layer chromatography indicated that the reaction was complete. After removal of the solid precipitate by filtration, the filtrate was concentrated and the residue recrystallized from acetone to give 306 mg (66%) of fine yellow needles: mp >240 °C; IR (KBr) $\nu_{C=O}$ 1675, 1690 cm^{-1}; NMR δ 10.21 (2 H, s, –CHO), 7.12 (2 H, s, ArH), 6.14 (2 H, s, ArH), 1.95 (6 H, s, $-CH_3$), 2.8–4.3 (8 H, m, $ArCH_3-$); UV (EtOH) λ_{max} 321 nm (ϵ 3860), 313 (3800), 363 (1640); mass spectrum *m/e* 292. Anal. ($C_{20}H_{20}O_2$) C,H.

When a sample of **7** was dissolved in glacial acetic acid containing a crystal of *p*-toluenesulfonic acid monohydrate and boiled under reflux for 10 min, concentration of the solution followed by recrystallization of the residual solid from acetone gave **11** in quantitative yield as fine yellow needles, identical in all of its properties with a sample of **11** prepared as described above.

[2.2.2.2](1,2,4,5)Cyclophane (9). A solution of 401 mg of **11** in 100 mL of dry tetrahydrofuran containing 540 mg of toluenesulfonohydrazide and 5 mg of *p*-toluenesulfonic acid was boiled under reflux for 1 h. After addition of 3.0 g of sodium methoxide with stirring, the resulting suspension was irradiated using a 400-W Hanovia lamp with a Pyrex filter. A gentle stream of nitrogen was maintained through the solution both for stirring and to provide a protective atmosphere. When the solution became colorless, the irradiation was stopped and 300 mL of water plus 200 mL of chloroform were added. The organic layer was then separated, washed with water, dried, and concentrated. The residual solid was chromatographed over silica gel using toluene for elution to give 260 mg (73%) of white plates: mp 350 °C (sealed capillary); IR (film) ν_{max} 2960, 1450, 1395, 930, 910, 730 cm^{-1}; UV (EtOH) λ_{max} 248 nm (sh, ϵ 3610), 294 (sh, 660), 303 (1050); NMR δ 5.96 (4 H, s, ArH), 2.5–3.5 (16 H, AA'BB' m, $ArCH_2-$); mass spectrum *m/e* 260. Anal. ($C_{20}H_{20}$) C,H.

Birch Reduction Product (14). A solution of 32 mg of **9** in 10 mL of tetrahydrofuran was added with stirring to a solution of 20 mg of lithium and 0.5 mL of *tert*-butyl alcohol in 40 mL of liquid ammonia. After the mixture had been stirred for 1 h, the blue color was discharged by addition of 1.0 mL of ethanol. When the ammonia had evaporated, the residue was extracted with dichloromethane, washed with water, dried, and concentrated. Sublimation of the crystalline residue gave 32.5 mg (100%) of white crystals: mp >200 °C dec.; IR (film) ν_{max} 2940, 2870, 2810, 1470, 1445, 1280, 1210 cm^{-1}; UV (EtOH) λ_{max} 295 nm (ϵ 85); NMR δ 1.8–2.8 (20 H, m, $-CH_2-C{=}C<$); mass spectrum *m/e* 264, 262, 260. Anal. ($C_{20}H_{24}$) C,H.

Addition of Dichlorocarbene to 14 to Give 15. To a solution of 50 mg of **14** in 20 mL of dichloromethane were added 10 mL of a 50% aqueous solution of potassium hydroxide, 30 mg of dimethylcetylbenzylammonium chloride, and 0.5 mL of chloroform. The mixture was stirred at room temperature for 1 week with daily additions of 10 mg of dimethylcetylbenzylammonium chloride and 0.5 mL of chloroform. Then the mixture was diluted with 100 mL of water and extracted with 200 mL of chloroform. The chloroform extract was washed with water, dried, and passed through a short column of silica gel. After concentration of the filtrate, the residual solid was suspended in a carbon tetrachloride solution, collected by filtration, and washed on the filter with 2 mL of acetone. This gave 63 mg (56%) of a white powder: mp >250 °C dec; IR (film) ν_{max} 2920, 1470, 925, 860 cm^{-1}; UV (CH_2Cl_2) λ_{max} end absorption only; mass spectrum *m/e* 600, 598, 596, 594, 592, 563, 561, 559, 557, 526, 524, 522. Anal. ($C_{24}H_{24}Cl_8$)

C,H.

Reduction of 15 to Give the Caged Hydrocarbon 16. A solution of 20 mg of **15**, 50 mg of lithium, and 0.5 mL of *tert*-butyl alcohol in 50 mL of tetrahydrofuran was boiled under reflux for 2 days. After removal of the excess lithium, 100 mL of water and 25 mL of dichloromethane were added. The organic layer was separated, washed with water, dried and concentrated. Sublimation (100 °C at 0.005 Torr) of the residue gave 5 mg (46%) of white needles: mp >270 °C dec; IR (film) ν_{max} 3040, 2840, 1470, 1025 cm^{-1}; NMR δ 0.00 (8 H, AB, $\Delta\nu$ = 0.28 ppm, J = 3 Hz), 1.3–2.5 (24 H, m); molecular weight calcd for $C_{24}H_{32}$ 320.250, found (high resolution mass spectrum) 320.252.

Diels–Alder Additions to 9. A. Addition of 1 Mol of Dicyanoacetylene to Give 17. A solution of 25 mg of **9** and 25 mg of dicyanoacetylene in 5 mL of chloroform was boiled under reflux for 6 h. The solution was then concentrated and the residual solid was purified by thin layer chromatography over silica gel using chloroform as eluant to give 30 mg (93%) of yellow needles: mp >250 °C dec; IR (film) ν_{max} 2960, 2920, 2310, 1590, 1440, 930 cm^{-1}; UV ($(CD_3)_2C(OH_2)$ λ_{max} 253 nm (sh, ϵ 4100), 299 (1100), 370 (242); NMR δ 6.71 (2 H, s, ArH), 3.89 (2 H, s), and 2.3–3.0 (16 H, m); molecular weight calcd for $C_{24}H_{20}N_2$ 336.163, found (high resolution mass spectrum) 336.162.

B. Addition of 2 Mol of Dicyanoacetylene to Give 18. A solution of 20 mg of **9** and 300 mg of dicyanoacetylene in 4 mL of benzene was heated at 70 °C for 2 days. The insoluble product was washed several times with benzene by decantation and then dried to give 24 mg (76%) of a yellow solid: mp >300 °C dec; IR (film) ν_{max} 2970, 2900, 2200, 1600, 1475, 1435, 1225, 1190, 1075, 950, 930 cm^{-1}; UV (CH_2Cl_2) λ_{max} 291 nm (ϵ 1000), 375 (500); NMR ($(CF_3)_2C(OD)_2$) δ 4.10 (4 H, s,), 2.0–3.0 (16 H, AA′BB′ m); molecular weight calcd for $C_{28}H_{20}N_4$ 412.169, found (high resolution mass spectrum) 412.173.

C. Addition of 2 Mol of Perfluoro-2-butyne to Give 19. A mixture of 20 mg of **9** and 0.2 mL of perfluoro-2-butyne in 0.2 mL of chloroform was heated in a sealed tube at 100 °C for 12 h. The resulting product was recrystallized from carbon tetrachloride to give 30 mg (66%) of fine white prisms: mp >300 °C dec; IR (film) ν_{max} 2900, 1690, 1660, 1300, 1250, 1190, 1140, 1010 cm^{-1}; UV (CH_3CN) λ_{max} 240 nm (sh, ϵ 700), 297 (160); NMR δ 4.04 (4 H, s), 2.0–3.0 (16 H, AA′BB′ m); mass spectrum *m/e* 594. Anal. ($C_{20}H_{28}F_{12}$) C,H.

D. Addition of Tetracyanoethylene to 17 to Give 22. A solution of 3.9 mg of **17** and 5 mg of tetracyanoethylene in 0.1 mL of chloroform was allowed to stand at room temperature for a brief period. The precipitate, which separated, was collected, washed with benzene, and dried to give 3 mg (46%) of a light tan powder: mp >200 °C dec; IR (film) ν_{max} 2890, 2200, 1600, 1470, 1435, 1230, 1190, 960 cm^{-1}; UV ($(CF_3)C(OH)_2$) λ_{max} 268 nm (ϵ 1600), 360 (350); NMR ($(CF_3)_2C(OD)_2$) δ 4.10 (2 H, s), 3.70 (2 H, s), 2.0–3.0 (16 H, m); mass spectrum *m/e* 336 ($M^+ - 128$ (C_6N_4)).

[2.2.2.2](1,2,4,5)Cyclophane 3,6-Epidioxide (23). A solution of 20 mg of **9** and 1 mg of methylene blue in 10 mL of chloroform was gently aerated for 7 min while being irradiated with a sun lamp. After passage over a short column of silica gel to remove the methylene blue, the eluate was concentrated and the residual solid purified by thin layer chromatography over silica gel using chloroform for elution. This gave 14.5 mg (65%) of white plates: mp 100 °C dec; IR (film) ν_{max} 2950, 2910, 1495, 1470, 1450, 1440, 1265, 845 cm^{-1}; UV (CH_2Cl_2) λ_{max} 298 nm (ϵ 1400); NMR δ 6.76 (2 H, s, ArH), 4.24 (2 H, s), 2.1–3.2 (16 H, m); molecular weight calcd for $C_{20}H_{20}O_2$ 292.131, found (high resolution mass spectrum) 292.130.

3,6-Dihydro[2.2.2.2](1,2,4,5)cyclophane-3,6-diol (24). To a solution of 5 mg of epidioxide **23** in 5 mL of tetrahydrofuran was added 5 mg of lithium aluminum hydride and the mixture was stirred at room temperature for 5 min. The suspension was then diluted with 50 mL of water and extracted with 25 mL of chloroform. The chloroform extract was washed with water, dried, and concentrated to give 5 mg (99%) of white crystals: NMR δ 6.70 (2 H, s, ArH), 3.72 (2 H, s), 2.1–3.2 (16 H, m); mass spectrum *m/e* 294 (molecular weight calcd for $C_{20}H_{22}O_2$ 294).

[2.2.2.2](1,2,4,5)Cyclophane-3-on-6-ol (25). A suspension of 17 mg of **23** and 300 mg of potassium hydroxide in 25 mL of methanol was stirred at room temperature for 12 h. The solution was then diluted with 25 mL of water and extracted twice with 20 mL portions of chloroform. The combined chloroform extracts were washed with water, dried, and concentrated. The residual solid was purified by preparative thin layer chromatography over silica gel using chloroform as eluant to give 15.5 mg (91%) of a white solid: mp 170 °C dec; IR (film) ν_{max} 3350, 2930, 1660, 1630, 995 cm^{-1}; UV (EtOH) λ_{max} 252 nm (ϵ 5300), 292 (2100); NMR δ 6.85 (1 H, s, ArH), 6.46 (1 H, s, ArH), 3.89 (1 H, d), 2.0–3.3 (16 H, m); mass spectrum *m/e* 292. Anal. ($C_{20}H_{20}O_2$) C,H.

[2.2.2.2](1,2,4,5)Cyclophane-3,6-dione (26). A solution of 15.5 mg of **25** and 300 mg of activated manganese dioxide[37] in 25 mL of chloroform was boiled under reflux for 4 days. After removal of the precipitate, the filtrate was concentrated and the residual solid purified by preparative thin-layer chromatography over silica gel using chloroform as eluant. This gave 13.5 mg (87%) of yellow needles: mp >300 °C dec; IR (film) ν_{max} 2950, 1645, 1250, 930 cm^{-1}; UV (CH_2Cl_2) λ_{max} 271 nm (ϵ 8800), 277 (8800), 300 (1960), 330 (1720); NMR δ 6.58 (2 H, s, ArH), 2.3–3.3 (16 H, m); mass spectrum *m/e* 290. Anal. ($C_{20}H_{18}O_2$) C,H.

1,2,4,5-Bis(cyclopropano)[2.2.2.2](1,2,4,5)cyclophane-3,6-dione (27). A solution of 30 mg of trimethylsulfoxonium iodide and a trace of triphenylmethane in 20 mL of dimethyl sulfoxide was titrated with a hexane solution of *n*-butyllithium to the point of first persistent red color. After the color was discharged by addition of a small amount of trimethylsulfoxonium iodide, a solution of 18 mg of **26** in 10 mL of dry tetrahydrofuran was added and the resulting solution was stirred for 24 h. The solution was the diluted with 30 mL of water and extracted with 30 mL of chloroform. The combined chloroform extracts were washed with water, dried, and concentrated. Purification of the residue by preparative thin-layer chromatography over silica gel using benzene as eluant gave 12.5 mg (63%) of white crystals: mp >270 °C dec; IR (film) ν_{max} 2940, 1670, 1450, 1025 cm^{-1}; UV (C_6H_{12}) λ_{max} 262 nm (sh, ϵ 1360), 287 (1100), 297 (1040); NMR δ 6.54 (2 H, s, ArH), 3.36 (4 H, septet), 2.5–3.1 (8 H, m), 1.26 (4 H, septet), 0.77 (4 H, AB, $\Delta\nu$ = 0.30 ppm, J = 5 Hz); mass spectrum *m/e* 318. Anal. ($C_{22}H_{22}O_2$) C,H.

1,2,4,5-Bis(cyclopropano)[2.2.2.2](1,2,4,5)cyclophane-*endo*-3,6-diol (28). A solution of 4 mg of **27** and 10 mg of lithium aluminum hydride in 10 mL of tetrahydrofuran was boiled under reflux for 6 h. After addition of 30 mL of water, the mixture was extracted with three 15-mL portions of chloroform. The combined chloroform extracts were dried and concentrated to give 4 mg (99%) of a white solid: mp >150 °C dec; IR ($CHCl_3$) ν_{max} 3610, 2920, 1480, 1460, 1085, 1085 cm^{-1}; UV (CH_2Cl_2) λ_{max} 294 nm (ϵ 1000); NMR δ 7.10 (2 H, s, ArH), 2.78 (4 H, AB, $\Delta\nu$ = 1.28 ppm, J = 8 Hz, -C*H*OH), −0.25 (4 H, AB, $\Delta\nu$ = 0.91 ppm, J = 4 Hz), 2.5–3.1 and 1.1–1.4 (16 H, m); molecular weight calcd for $C_{22}H_{26}O_2$ 322.193, found (high resolution mass spectrum) 322.192.

1,2,4,5-Bis(cyclopropano)(2.2.2.2](1,2,4,5)cyclophane-*exo*-3,6-diol (30). A solution of 11 mg of **28** and 0.1 mL of thionyl chloride in 2 mL of pyridine was allowed to stand at room temperature for 1 h. It was then diluted with 20 mL of water and extracted with five 10-mL portions of chloroform. The combined chloroform extracts were dried and concentrated to give 7 mg (64%) of a light tan solid: NMR δ 7.04 (2 H, s, ArH), 4.38 (2 H, s, -C*H*OH), −0.22 (4 H, AB, $\Delta\nu$ = 0.02 ppm, J = 4 Hz), 1.2–1.5 and 2.3–3.1 (16 H, m); mass spectrum *m/e* 322, 320, 318.

The exo diol **30** is quite labile and could not be purified further. Its equilibrium with the corresponding exo dichloride **29** was shown by its behavior in solution in an NMR probe. Treatment of the endo diol **30** with thionyl chloride gave rise to a ^{1}H NMR spectrum (δ 7.05 (2 H, s, ArH), 4.96 (2 H, s, -CHCl), 0.31 (4 H, AB, $\Delta\nu$ = 0.24 ppm, J = 6 Hz), 1.2–1.5 and 2.3–3.1 (16 H, m)) corresponding to the exo dichloride **29**. Addition of water causes reversion to the spectrum of the exo diol **30** and this, in turn, on exposure to fumes of hydrogen chloride gas, reverts to the spectrum of the exo dichloride **29**.

Addition of Ethyl Diazoacetate to [2.2.2.2](1,2,4,5)Cyclophane to Give 33. A solution of 30 mg of **9**, 25 μL of ethyl diazoacetate, and 10 mg of anhydrous cupric sulfate in 10 mL of dry chloroform (ethanol-free) was boiled under reflux until its yellow color was discharged. The mixture was then concentrated and the resiude was extracted with ethyl acetate by decantation. The residue was then combined with 20 μL of ethyl diazoacetate and 10 mg of anhydrous cupric sulfate in 10 mL of dry chloroform and again boiled under reflux until the yellow color disappeared. The mixture was then combined with the previous ethyl acetate extract and concentrated. Subjection of the resulting residue to preparative thin-layer chromatography over silica gel using benzene for elution led to a recovery of 8 mg of starting material before the main fraction of eluate which gave 11.5 mg (39%) of a white solid:

mp 156–157 °C; IR (film) ν_{max} 2940, 1695, 1260, 1220, 760 cm^{-1}; UV (EtOH) λ_{max} 293 nm (ϵ 9400); NMR δ 6.97 (1 H, s, -C*H*=C-CO_2Et), 6.70 (1 H, s, ArH), 6.23 (1 H, s, ArH), 4.05 (2 H, q, J = 7 Hz), 1.33 (3 H, t, J = 7 Hz), 1.5–3.3 (18 H, m); molecular weight calcd for $C_{24}H_{26}O_2$ 346.193, found (high resolution mass spectrum) 346.195.

Since the ^{1}H NMR spectrum of the product did not clearly distinguish between **32** and **33** as possible structures, the ^{13}C NMR spectrum was taken. Again, for lack of suitable reference compounds, the ^{13}C NMR spectrum was not definitive. The preparation of **33** was then repeated using ethyl diazoacetate enriched with carbon-13 at the carbonyl and methine carbons. The ^{1}H NMR spectrum of this product was unaffected by the carbon-13 labeling except for the signal at δ 6.97 which was now split into a broad doublet. This is in agreement with its assignment as the β-vinyl hydrogen in structure **33**. The ^{13} NMR spectrum of the carbon-13-enriched preparation showed the enriched signals as an AB quartet at δ 135.0 and 169.4 (downfield from Me_4Si, J = 70.6 Hz) which is appropriate for the labels to be at the carbonyl carbon and the attached vinyl carbon. Thus, the ^{13}C NMR spectrum of the carbon-13-enriched product clearly defines the structure as being **33**.

Reduction of 33 to Give 34. A solution of 11.5 mg of **33** and 10 mg of lithium aluminum hydride in 10 mL of dry tetrahydrofuran was boiled under reflux for 30 min. The mixture was then diluted with 30 mL of water and extracted with two 20-mL portions of chloroform. The combined chloroform extracts were washed with water, dried, and concentrated to give 10.5 mg (99%) of an air-sensitive white solid: mp 168–172 °C; NMR δ 6.66 (1 H, s), 6.13 (1 H, s), 6.04 (1 H, s), 4.30 (2 H, AB, $\Delta\nu$ = 0.45 ppm, J = 12 Hz), 1.6–3.3 (18 H, m); UV (EtOH) λ_{max} 280 nm (ϵ 3300); molecular weight calcd for $C_{22}H_{24}O$ 304.183, found (high resolution mass spectrum) 304.183.

Conversion of 34 to 36. When a solution of 10.5 mg of **34** in 0.1 mL of deuteriochloroform in an NMR tube was treated with 1 drop of thionyl chloride, the ^{1}H NMR spectrum of the solution changed from that of the alcohol **34** to a spectrum (δ 6.66 (1 H, s), 6.20 (1 H, s), 6.15 (1 H, s), 4.24 (2 H, AB, $\Delta\nu$ = 0.38 ppm, J = 11 Hz), 1.6–3.3 (18 H, m)) appropriate to the chloro derivative **35**. After concentration of the reaction mixture, the residue was taken up in 10 mL of tetrahydrofuran and 10 mg of lithium aluminum hydride was added immediately. The solution was then boiled under reflux for 30 min, 1 mL of methanol and 20 mL of water were added, and the mixture was extracted with 20 mL of chloroform. Concentration of the chloroform extract followed by preparative thin-layer chromatography of the residue over silica gel using carbon tetrachloride for elution gave 7.5 mg (75% overall) of a white solid: mp very broad; IR (film) ν_{max} 2960, 1460, 1450, 1440, 1405 cm^{-1}; UV (EtOH) λ_{max} 278 nm (ϵ 3450); NMR δ 6.64 (1 H, s), 6.18 (1 H, s), 5.86 (1 H, s), 1.93 (3 H, s), 1.6–3.2 (18 H, m); and molecular weight calcd for $C_{22}H_{24}$ 288.188, found (high resolution mass spectrum) 288.187.

Preparation of the Polymer Reagent Containing Triphenylmethyl Fluoroborate Groups. A sample of Rohm and Haas amberlite XE-305[38] was ground to 100-mesh size by a ball mill. A mixture of 100 mg of the finely ground polymer, 1 mL of benzoyl chloride, and 1 mL of stannic chloride in 25 mL of dichloromethane was stirred at room temperature for 1 h. After the reaction mixture had been quenched by addition of 50 mL of water, the insoluble polymer was collected by filtration, washed successively with water and benzene, and dried. The dry polymer was then stirred with a solution of 1 mL of 1.88 M solution of phenyllithium in benzene in 25 mL of benzene for 1 h. The polymer was again collected by filtration and stirred for 3 h with 10 mL of a 48% aqueous solution of fluoroboric acid. The orange-red polymer was then collected by filtration and carefully dried under vacuum.

[2.2.2.2](1,2,4,5)-7′-Methyltropyliparacyclophane (37). A mixture of 200 μg of **36** and 5 mg of the polymer reagent containing triphenylmethyl fluoroborate groups was placed in an NMR tube and evacuated at 10^{-5} mm for 4 h. Perdeuterioacetonitrile was vacuum transferred into the tube and the NMR tube was sealed under vacuum. The solution rapidly became colored and its NMR spectrum (see Figure 1) showed signals at δ 8.06 (1 H, s), 7.70 (1 H, s), 6.94 (1 H, s), 5.70 (1 H, s), 2.81 (3 H, s), 2.5–3.9 (16 H, m).

For the ultraviolet and visible spectrum of **37**, the preparation was repeated as before using acetonitrile as solvent but with an apparatus that allowed the solution, after completion of the reaction, to be separated from the polymer reagent and collected in an optical cell for the Cary 15 spectrophotometer. Measurement of the ultraviolet and visible spectrum of **37** showed λ_{max} 351 nm (ϵ 2000) and 460 (sh, 440). The values for the extinction coefficients are based on the assumption that the conversion of **36** to **37** by this technique is quantitative.

When the reaction of **36** with triphenylmethyl fluoroborate itself was tried, it was found that separation of **37** from the reagent led to apparent reaction with adventitious moisture producing a new product of unknown structure.

Photoisomerization of 17 to Give 38 (or 39?). A solution of 23 mg of **17** in 20 mL of tetrahydrofuran was placed in a quartz tube, carefully degassed, and sealed under vacuum. It was then irradiated with a low pressure mercury lamp for 2.5 h. After concentration of the solution, the residual solid was purified by preparative thin-layer chromatography over silica gel using chloroform as eluant to give 9.5 mg (41%) of pale yellow needles: mp >180 °C dec; IR (film) ν_{max} 2940, 1650, 1600, 1505, 1475, 1455, 1445, 910 cm^{-1}; UV (CH_2Cl_2) λ_{max} 260 nm (ϵ 4160), 318 (1035); NMR δ 6.72 (2 H, s, ArH), 6.12 (2 H, s, -CH=C<), 1.93–3.4 (16 H, m); molecular weight calcd for $C_{24}H_{20}N_2$ 336.163, found (high resolution mass spectrum) 336.163.

Acknowledgment. We thank the National Science Foundation for their support of this investigation.

References and Notes

(1) A preliminary account of this work has been reported: R. Gray and V. Boekelheide, *Angew. Chem.*, **87**, 138 (1975); *Angew. Chem., Int. Ed. Engl.*, **14**, 107 (1975)).
(2) C. J. Brown and A. C. Farthing, *Nature (London)*, **164**, 915 (1949); cf. D. J. Cram and H. Steinberg, *J. Am. Chem. Soc.*, **73**, 5691 (1951).
(3) (a) D. J. Cram and J. M. Cram, *Acc. Chem. Res.*, **4**, 204 (1971); (b) F. Vögtle and G. Hohner, *Top. Curr. Chem.*, **74**, 1 (1978).
(4) (a) W. S. Lindsay, P. Stokes, L. G. Humber, and V. Boekelheide, *J. Am. Chem. Soc.*, **83**, 943 (1961); (b) D. J. Kamp and V. Boekelheide, *J. Org. Chem.*, **43**, 3470 (1978).
(5) D. J. Cram, R. C. Helgelson, D. Lock, and L. A. Singer, *J. Am. Chem. Soc.*, **88**, 1324 (1966).
(6) V. Boekelheide, P. A. Anderson, and T. A. Hylton, *J. Am. Chem. Soc.*, **96**, 1558 (1974); cf. S. A. Sherrod, R. L. da Costa, R. A. Barnes, and V. Boekelheide, *ibid.*, **96**, 1565 (1974).
(7) V. Boekelheide and R. A. Hollins, *J. Am. Chem. Soc.*, **92**, 3201 (1970).
(8) (a) E. A. Truesdale and D. J. Cram, *J. Am. Chem. Soc.*, **95**, 5825 (1973); (b) S. Trampe, H. Hopf, and K. Menke, *Chem. Ber.*, **110**, 371 (1977).
(9) M. Nakazaki, K. Yamamoto, and Y. Miura, *J. Org. Chem.*, **43**, 1041 (1978).
(10) Recently, W. Gilb, K. Menke, and H. Hopf (*Angew. Chem.*, **89**, 177 (1977); *Angew. Chem., Int. Ed. Engl.*, **16**, 191 (1977)) have reported the synthesis of another tetrabridged example, [2.2.2.2](1,2,3,5)cyclophane.
(11) (a) R. H. Mitchell and V. Boekelheide, *J. Am. Chem. Soc.*, **96**, 547 (1974); (b) V. Boekelheide, I. D. Reingold, and M. Tuttle, *J. Chem. Soc., Chem. Commun.*, 406 (1973).
(12) H. J. Reich and D. J. Cram, *J. Am. Chem. Soc.*, **91**, 3505, 3517, 3527 (1969).
(13) D. J. Cram, R. B. Hornsby, E. A. Truesdale, H. J. Reich, and M. H. Delton, *Tetrahedron*, **30**, 1757 (1974).
(14) Since completion of this work, a much shorter and more convenient route to [2.2.2.2](1,2,4,5)cyclophane has been developed; see V. Boekelheide and G. Ewing, *Tetrahedron Lett.*, 4245 (1978).
(15) D. J. Cram, R. H. Bauer, N. L. Allinger, R. A. Reeves, W. J. Wechter, and E. Heilbronner, *J. Am. Chem. Soc.*, **81**, 5977 (1959).
(16) V. Boekelheide and R. A. Hollins, *J. Am. Chem. Soc.*, **95**, 3201 (1973).
(17) A. W. Hanson, *Acta Crystallogr., Sect. B*, **33**, 2003 (1977).
(18) C. L. Coulter and K. N. Trueblood, *Acta Crystallogr.*, **16**, 667 (1963).
(19) It is known from the work of Professor Misumi (H. Iwamura, H. Kihara, S. Misumi, Y. Sakata, and T. Umemoto, *Tetrahedron Lett.*, 615 (1976)) that it takes less energy to deform a benzene ring to a boat conformation than to a chair conformation.
(20) H. J. Lindner, *Tetrahedron*, **32**, 753 (1976).
(21) M. Makosza and M. Wawrzyniewicz, *Tetrahedron Lett.*, 4659 (1969).
(22) M. J. Goldstein and R. Hoffman, *J. Am. Chem. Soc.*, **93**, 6193 (1971).
(23) (a) R. C. Cookson and J. Dance, *Tetrahedron Lett.*, 879 (1962); (b) C. D. Weis, *J. Org. Chem.*, **28**, 74 (1963).
(24) C. G. Krespan, B. C. McKusick, and T. L. Cairns, *J. Am. Chem. Soc.*, **83**, 3428 (1961).
(25) W. G. Dauben and G. H. Berezin, *J. Am. Chem. Soc.*, **85**, 468 (1963).
(26) E. J. Corey and M. Chaykovsky, *J. Am. Chem. Soc.*, **87**, 1353 (1965).
(27) H. Kessler and W. Ott, *Tetrahedron Lett.*, 1383 (1974).
(28) (a) K. Menke and H. Hopf, *Angew. Chem.*, **88**, 152 (1976); *Angew. Chem., Int. Ed. Engl.*, **15**, 165 (1976). (b) R. Näder and A. de Meijere, *Angew. Chem.*, **88**, 153 (1976); *Angew. Chem., Int. Ed. Engl.*, **15**, 166 (1976).
(29) H. Horita, T. Otsubo, Y. Sakata, and S. Misumi, *Tetrahedron Lett.*, 3899 (1976).
(30) J. G. O'Connor and P. M. Keehn, *J. Am. Chem. Soc.*, **98**, 8446 (1976).
(31) The idea for using such a polymeric reagent was derived from another example of a polymeric reagent reported by B. J. Cohen, *J. Am. Chem. Soc.*, **99**, 4165 (1977).
(32) H. E. Zimmerman, R. W. Binkley, R. S. Givens, G. L. Grunewald, and M. A. Sherwin, *J. Am. Chem. Soc.*, **91**, 3316 (1969).
(33) Elemental and mass spectral analyses were determined by Dr. S. Rottschaefer and Dr. R. Wielesek of the University of Oregon Microanalytical Laboratories. Melting points were taken with a Mel-Temp apparatus

and are uncorrected. Infrared spectra were obtained with a Beckman IR-7 apparatus, and visible and ultraviolet spectra with a Cary 15 spectrophotometer. NMR spectra were measured with a Varian XL-100 instrument using deuteriochloroform as solvent and with residual chloroform (δ 7.27) as an internal standard. Mass spectra were obtained using a CEC-21B-110 instrument set at 70 eV.

(34) K. Murao, S. Tanimoto, and R. Oda, *Kogyo Kagaku Zasshi*, **66**, 1538 (1963); *Chem. Abstr.*, **60**, 11926 (1963).
(35) M. Masamura, T. Horie, and M. Tsukayana, *Kogyo Kagaku Zasshi*, **72**, 682 (1969); *Chem. Abstr.*, **72**, 66544 (1970).
(36) M. Cachia and H. Wahl, *Bull. Soc. Chim. Fr.*, 1418 (1958).
(37) J. Attenburrow, A. F. B. Cameron, J. H. Chapman, R. M. Evans, B. A. Hens, A. B. A. Jansen, and T. Walker, *J. Chem. Soc.*, 1094 (1952).
(38) We thank Dr. A. R. Pitochelli of the Rohm and Haas Co. for his kindness in providing us with a sample of the Amberlite XE-305 macroreticular polystyrene resin.

2,2-Dimethylisoindene and 5,5-Dimethylbenzobicyclo[2.1.0]pent-2-ene

William R. Dolbier, Jr.,*[1a] Kazumasa Matsui,[1a] Harry J. Dewey,[1b] David V. Horák,[1c] and Josef Michl*[1b]

Contribution from the Departments of Chemistry, University of Utah, Salt Lake City, Utah 84112, and University of Florida, Gainesville, Florida 32611.
Received September 5, 1978

Abstract: 2,2-Dimethylisoindene (**1**) is quite stable in solution at room temperature in the absence of oxygen. It can be prepared from the azoxy precursor **3** by irradiation in a glassy matrix or by room temperature deoxygenation with Si_2Cl_6, and from the dibromo precursor **4** by reaction with metals. The photochemical interconversion **1** $\rightleftharpoons$ **2** is described; the activation energy for the facile thermal "forbidden" ring opening **2** $\rightarrow$ **1** is 18.9 kcal/mol. The NMR, UV, fluorescence, polarized excitation and emission, and MCD spectra of **1** are reported. Comparison with semiempirical calculations using singly and doubly excited configurations shows good agreement and suggests the presence of a low-energy "doubly excited" state, believed to be responsible for the photochemical reactivity of **1**.

Introduction

The highly reactive *o*-xylylene[2,3] and its various simple derivatives[4,5] have been generated, trapped, and characterized spectroscopically, and some have been even isolated in solution. On the other hand, related simple isoindenes, although generated and trapped,[6,7] have eluded direct characterization until a short time ago.[8] In recent short communications,[9,10] two research groups have reported the isolation and spectral properties of solutions of 2,2-dimethyl-2*H*-indene (2,2-dimethylisoindene, **1**), and a full report on flash photolytic experiments which allowed the direct observation of several arylisoindenes by absorption spectroscopy has just appeared.[11] Similarly as other *o*-xylylenes,[2,5] **1** can be converted photochemically to the corresponding benzocyclobutene[9] (**2**). This highly strained tricyclic ring system is believed to have been first generated some time ago by Berson and Pomerantz[12] by addition of benzyne to a cyclopropene (they proposed the name pseudoindene). In the present paper, we describe the preparation and properties of both **1** and **2**, as well as their facile mutual interconversion.

Results

We have found three methods useful for generation of **1** from easily accessible precursors. In the order of discovery as well as increasing convenience, these were (1) irradiation of the azoxy compound **3**[7] in an EPA glass matrix at 77 K, (2) deoxygenation of **3** with Si_2Cl_6 at room temperature with concurrent loss of N_2, (3) dehalogenation of the dibromo derivative **4** with metals at room temperature, all in the absence of oxygen.

The photochemical conversion **3** $\rightarrow$ **1** in rigid matrix can be accomplished both with a low-pressure mercury arc, which excites the benzene chromophore, and with a high-pressure mercury lamp using a $\lambda > 285$ nm filter, which excites primarily the azoxy chromophore. Only relatively low concentrations can be achieved by this method. Once produced, the solution of **1** is stable even at room temperature as long as no oxygen is present. However, room temperature or dry ice temperature irradiation of a fluid solution of **3** in EPA, ether, or ethanol ($\lambda > 285$ nm) produces only traces of **1**. The major product at -80 °C is a mixture of two species containing the benzene chromophore (UV) and stable for days at -80 °C but reconverting to **3** after several hours at -20 °C and faster at room temperature. The return to **3** was not affected by thorough removal of all gases present (freeze–pump–thaw), proving that the two new species still contain the elements of N_2O and are isomeric with **3**. The NMR spectrum (CD_3OD) showed that the photoisomers were formed in a ratio of about 2.5:1. Both contribute to a narrow multiplet at δ 7.38 (4 H); the major isomer also has singlets at δ 4.64 (2 H), 1.50 (3 H), and 0.57 (3 H), and the minor one also has singlets at δ 4.81 (2 H), 1.44 (3 H), and 0.60 (3 H). Based on these data, we propose the structures of endo and exo oxadiaziridines **5a** and **5b** to these unstable products. There is good precedent for photocyclization of acyclic azoxy compounds to oxadiaziridines,[13] though cyclic (cis) azoxy compounds have apparently not been previously transformed in this fashion.

The deoxygenation of **3** with neat Si_2Cl_6[14] in the absence of oxygen proceeds smoothly at room temperature and provides much more concentrated yellow solutions of **1**. Unfortunately, the Si_2Cl_6 solvent interferes with some spectroscopic measurements and is difficult to remove. However, these solutions were suitable for chemical proofs of the structure of **1**. Treatment with HCl or with dimethyl maleate causes a rapid disappearance of the yellow color. Isolation yielded the chloroderivative **6** and the diester **7**, respectively. These were fully characterized and identified by comparison with authentic samples.

The dehalogenation of **4** with metals proceeds smoothly at room temperature. Zinc–copper couple and lithium amalgam are particularly suitable reagents. Absolute exclusion of oxygen is again essential. The reaction can be performed in volatile

0002-7863/79/1501-2136$01.00/0