

1-(2,4-Dimethylphenyl)-1-phenylethanol. To a solution of 0.325 g (1.15 mmol) of 2,4-dimethylbenzophenone in 10 mL of ether was added 2.86 mmol of CH_3MgBr in 2.6 mL of ether. After 7 h the reaction was hydrolyzed with saturated $\text{NH}_4\text{Cl}/\text{H}_2\text{O}$. The mixture was dried and the ether was removed. The product was shown to be >95% pure by NMR spectroscopy (CDCl_3 , Me_4Si): 8 H multiplet at δ 6.8 to 7.7, 3 H singlet at 1.83, 3 H singlet at 1.93, 3 H singlet at 2.28, 1 H singlet at 2.20.

1-(2,5-Dimethylphenyl)-1-phenylethanol. To a solution of 0.0541 g (0.259 mmol) of 2,5-dimethylbenzophenone in 10 mL of ether was added 0.465 mmol of CH_3MgBr in 0.20 mL of ether. After 4 h the reaction was hydrolyzed with saturated $\text{NH}_4\text{Cl}/\text{H}_2\text{O}$. The mixture was dried and the ether removed. The product was shown to be >95% pure by NMR spectroscopy (CDCl_3 , Me_4Si): 8 H multiplet at δ 7.0–7.6, two 3 H singlets close together at 1.88 and 1.90, 3 H singlet at 2.38, 1 H broad singlet at 2.17.

Methods. Apparatus and Procedure. A Varian A-60D, 60-MHz spectrometer was used for recording nuclear magnetic resonance spectra. GLC analyses were carried out on F & M Models 700 and 720 gas chromatographs. Materials used in this study were transferred in a glove box described elsewhere¹⁶ or in Schlenk tubes under a blanket of nitrogen.

Calibrated syringes equipped with stainless steel needles were used for transfer of reagents. Ketone and metal salt solutions were prepared by weighing the reagent in a tared volumetric flask and diluting with the appropriate solvent. All metal solutions were used within 24 h of preparation.

Reactions in General. Glassware and syringes were flamed and taken into a glove box under vacuum. The appropriate amounts of solvent and ketone solutions were syringed into a septum capped test tube. An appropriate amount of Grignard solution was added with swirling. In these cases in which the reaction was carried out in the presence of an iron salt, the salt was added immediately prior to addition of the Grignard reagent. In general, these reactions used 0.10 mmol of enone and 0.05 mmol of organometallic reagent in 1.5 mL of ether. The rate studies used 0.05 mmol of enone and 0.05 mmol of Grignard reagent in 2.0 mL of ether. After an appropriate reaction time, usually 20 min, the reactions were hydrolyzed with 50 mL of saturated NH_4Cl solution and dried over MgSO_4 .

The identification of all the products from the reactions with cis and trans enone was determined by GLC on a 12-ft 20% Carbowax 20M column at 125 °C; injection port temperature, 180 °C; detector temperature, 240 °C; and helium flow rate, 80 mL/min were generally

used. Retention times varied with conditions, but typically were as follows: dodecane, 10.3, cis enone, 12.6, trans enone, 14.9, methyl 1,4-addition product, 17.4, methyl trans-1,2-addition product, 19.7, cis- and trans-1,2-reduction product, 24.8, allyl trans-1,2-addition product, 34.0, allyl cis-1,2-addition product, 50.8, *tert*-butyl trans-1,2-addition product, 38.9, *tert*-butyl 1,4-addition product, 42.9, *tert*-butyl cis-1,2-addition product, 68.6 min. Dodecane was employed as internal standard and relative response factors were determined regularly. In some cases cis- and trans-1,2-reduction products were separated on a 12-ft 10% TCEP column at 115 °C, but generally they were analyzed together and identified as "1,2-reduction products".

In general, these reactions had essentially 100% material balances.

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Mechanistic Aspects of Transition Metal and Trichloroacetic Acid Catalyzed Reactions of 3-Oxaquadricyclanes

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Abstract: The reactivity of 1,5-dicarbomethoxy-3-oxaquadricyclanes toward different catalysts has been found to vary strongly with the type of catalyst used. The various reactions initiate at different sites in the substrates: CCl_3COOH reacts at a cyclopropyl ring atom with inversion of configuration; $\text{Rh}_2(\text{CO})_4\text{Cl}_2$ reacts preferentially as a Lewis acid at the C–O–C fragment; to a minor extent oxidative addition of a cyclopropyl ring to the rhodium(I) complex occurs as in the case of the $\text{Pd}(\text{C}_6\text{H}_5\text{CN})_2\text{-Cl}_2$ catalyzed reaction; a kinetic analysis shows that the AgClO_4 catalyzed reaction initiates at two sites (at the C–O–C fragment and at a cyclopropyl ring), both leading to the same reaction product. Compound **1b** reacts much faster than **1a** in the thermal and CCl_3COOH catalyzed reactions in contrast to the metal catalyzed processes.

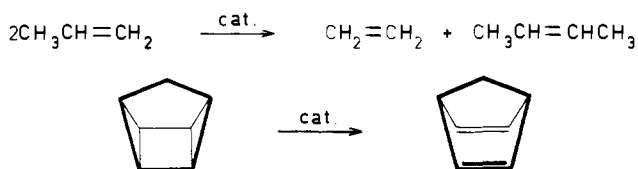
Introduction

For more than a decade there has been much interest in the interconversion between two ethylene units and a cyclobutane unit catalyzed by transition metal complexes. In 1964 the first report on olefin disproportionation (metathesis) ap-

peared (the conversion of propylene into ethylene and 2-butene over a molybdenum hexacarbonyl–alumina catalyst)¹ and in 1967 the valence isomerization of quadricyclane into norbornadiene was reported² (Scheme I).

Much experimental and theoretical work has been carried out, as a result of which the original idea of a common under-

Scheme I



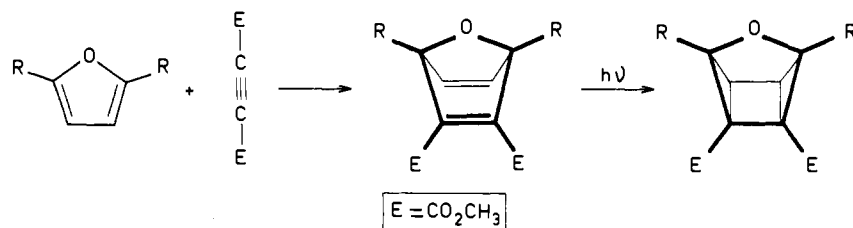
lying mechanism for these processes has been abandoned.³⁻⁹ The fact that olefins substituted with heteroatoms have generally been found to show no or a reduced tendency for olefin disproportionation¹⁰—probably because of saturation of the metal coordination sites by the heteroatom lone pairs¹¹—combined with the observation that 3-oxaquadricyclanes do not give the same type of product on treatment with catalytic amounts of $\text{Rh}_2(\text{CO})_4\text{Cl}_2$ as do quadricyclanes¹² made us already decide some time ago to start a study about the reactivity of 3-oxaquadricyclanes toward various catalysts.

3-Oxaquadricyclanes are synthesized by photochemical cyclization of the corresponding 7-oxanorbodienes,¹³ which in turn are prepared by a Diels-Alder reaction of suitably substituted furans and acetylenes¹⁴ (Scheme II). In contrast to the reactivity of cubane,¹⁵ homocubane,¹⁶ bishomocubane,¹⁷ and bicyclobutane derivatives,¹⁸ that of 3-oxaquadricyclanes toward transition metal complexes or proton acids has not been the subject of a thorough investigation, although these strained

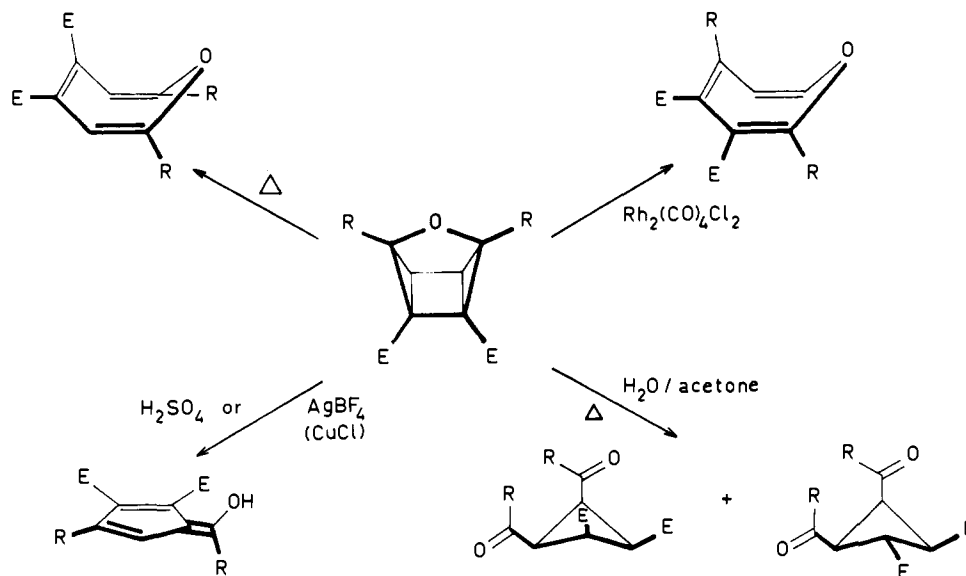
species are of interest, because they possess various reactive sites. It has been reported¹⁹ that treatment of 3-oxaquadricyclanes in methylene chloride solution with sulfuric acid gives rise to the formation of 6-hydroxyfulvenes. These products are also obtained when methylene chloride solutions of 3-oxaquadricyclanes are treated with AgBF_4 or CuCl ,²⁰ or when 3-oxaquadricyclanes are treated with catalytic amounts of $\text{Rh}_2(\text{CO})_4\text{Cl}_2$ in solutions of commercially available deuteriochloroform (Scheme III).¹² Subsequently, it has been pointed out that the latter conversions are not truly $\text{Rh}_2(\text{CO})_4\text{Cl}_2$ catalyzed processes, but the result of impurities in the solvent. When carefully purified chloroform is used in this reaction, the main products are oxepine derivatives,²¹ different from the ones which are obtained by thermal decomposition of the 3-oxaquadricyclanes.^{13a} Refluxing of 3-oxaquadricyclanes in a water-acetone mixture has been reported to afford a mixture of substituted, isomeric cyclobutanes.²² Although in the cited papers not much mechanistic information has been gathered, it is most commonly assumed that the reactions occur via attack of the catalyst on the ether oxygen atom.^{21,22}

In the present paper we will focus our attention on the question of how and where the various catalysts will attack a 3-oxaquadricyclane molecule. In principle four different bonds can be broken by attack of a catalyst on the molecule (denoted as a, b, c, and d in the structure of **1** (Scheme IV): a C-O bond and three different bonds of a cyclopropyl ring. In order to

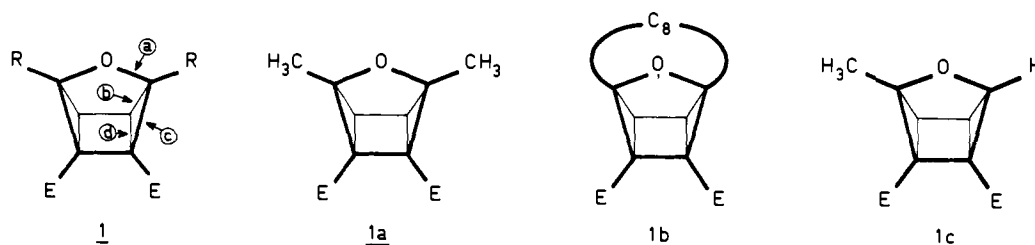
Scheme II



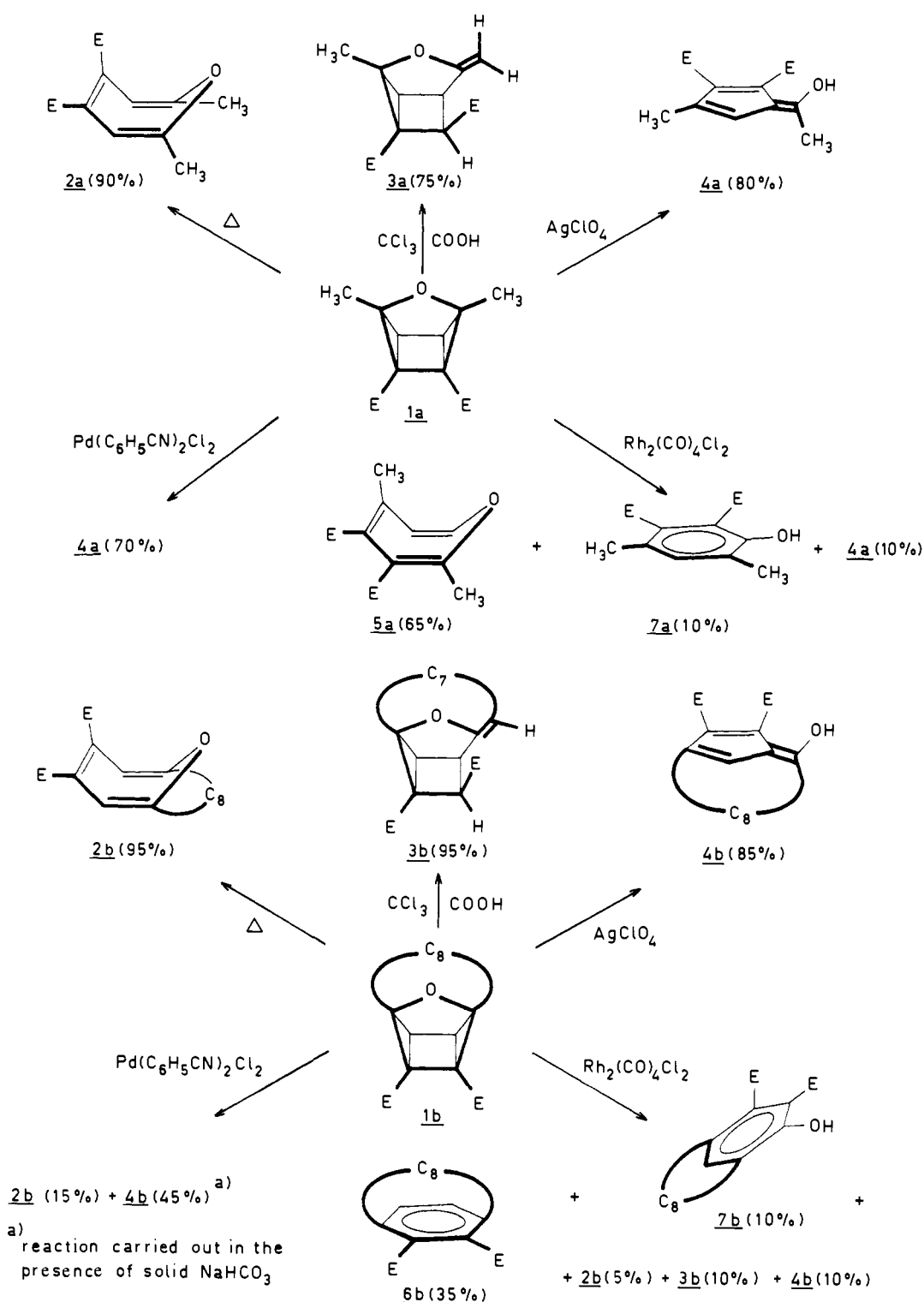
Scheme III



Scheme IV



Scheme V



reduce the probability of attack on the C–O–C fragment as compared with attack on a site of cyclopropyl ring, we have synthesized a 3-oxaquadricyclane derivative containing an octamethylene chain (**1b**). The results of the reactions of **1a**, **1b**, and **1c** with CCl₃COOH, AgClO₄, Pd(C₆H₅CN)₂Cl₂, and Rh₂(CO)₄Cl₂ in benzene solution have been used to elucidate the mechanistic details of the catalyzed processes.²³

Results

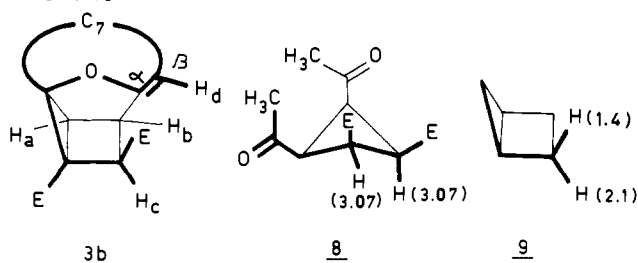
In Scheme V the results are summarized of the reactions of **1a**²⁴ and of **1b** (0.30 mol/L) with the various catalysts (0.030 mol/L) in benzene solution. The thermal stability of **1b** is

Table I. Relative Rates of Compounds **1a** and **1b** (0.3 mol/L) and Half-Lives of **1a** for the Various Reactions in Benzene Solution (Catalyst Concentration 0.03 mol/L)

Reaction	rel.rate ($\underline{1a}/\underline{1b}$)	half-life $\underline{1a}$ (h)	temp.(°C)
thermal dec	0.006	70	72
CCl ₃ COOH	0.008	1	20
AgClO ₄	2	0.3	27
Rh ₂ (CO) ₄ Cl ₂ ^a	0.25	0.5	40
Pd(C ₆ H ₅ CN) ₂ Cl ₂	7	7	20

^a Concentration of **1a** and **1b**, 0.2 mol/L.

Scheme VI

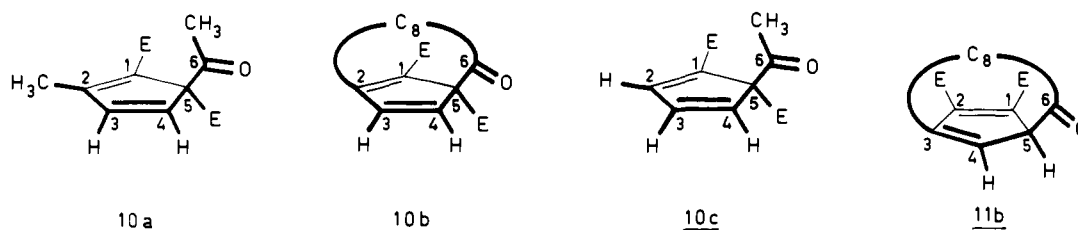


smaller than that of **1a** (Table I), which is responsible for the occurrence of **2b** in the palladium and rhodium catalyzed reactions of **1b**. When compounds **1a** and **1b** are treated with CCl_3COOH , they are converted into compounds **3a** and **3b**, respectively, the reaction of **1a** being much slower than that of **1b** (Table I). Compound **3b** is also obtained as the main reaction product when **1b** is treated with $\text{Pd}(\text{C}_6\text{H}_5\text{CN})_2\text{Cl}_2$. However, if solid NaHCO_3 is added to the reaction mixture, no formation of **3b** is observed and the 6-hydroxyfulvene **4b** is the main reaction product, analogous to the formation of **4a** from **1a** on treatment with the palladium catalyst.²⁵ 6-Hydroxyfulvenes **4a** and **4b** are also formed when **1a** and **1b** are treated with AgClO_4 , the reaction of **1a** being two times faster than that of **1b** (Table I). Treatment of **1a** with $\text{Rh}_2(\text{CO})_4\text{Cl}_2$ leads to the formation of **5a** as main product, whereas, in the case of **1b**, the main product proves to be **6b**. The reactions of **1a** and **1b** with AgClO_4 have also been carried out in methanol solution,²⁶ affording the same products—**4a** (yield 50%) and **4b** (yield 90%), respectively—as in benzene solution (Scheme V).

Discussion

A. Structural Assignments.²⁷ The white crystalline compound **3b** has been characterized by elemental analysis, mass number, and ^{13}C and ^1H NMR spectroscopy. The ^{13}C NMR chemical shift of the β -carbon atom is found to be 97.8 ppm, which agrees with literature values.²⁸ The values of the observed coupling constants $J(\text{C}-\text{H}_a) = 193$, $J(\text{C}-\text{H}_b) = 157$, $J(\text{C}-\text{H}_c) = 143$, and $J(\text{C}-\text{H}_d) = 163$ Hz are in good agreement with reported data.²⁹ The ^1H NMR spectrum reveals only 14 (rather than 16) aliphatic hydrogens, which can be assigned to the octano chain of **3b**, indicating in consequence that the double bond is located in this segment. The chemical shift of H_d at δ 4.30 indicates that this hydrogen is trans to the oxygen atom,³⁰ which agrees with an inspection of molecular framework models. The configuration around the cyclobutane carbon atom, bearing H_c and an ester substituent, has been elucidated by comparison of the ^1H NMR chemical shift of H_c (δ 3.8 in **3b**) with the reported ^1H NMR data of compounds **8**²² and **9**.³¹ This assignment is based upon the following reasoning: in case H_c in compound **3b** was to possess the orientation opposite to that indicated in the structure, one would have expected a chemical shift smaller than δ 3.07 (this being the value in **8**) because of the upfield shifting both by the cyclopropyl ring (compare the relative values of δ 2.1 and 1.4 in **9**) and by the $-\text{O}-\text{C}=\text{C}-$ fragment, as indicated by model inspection. Actually the chemical shift of H_c is found to be δ 3.8 and therefore H_c must possess the orientation as indicated in

Scheme VII



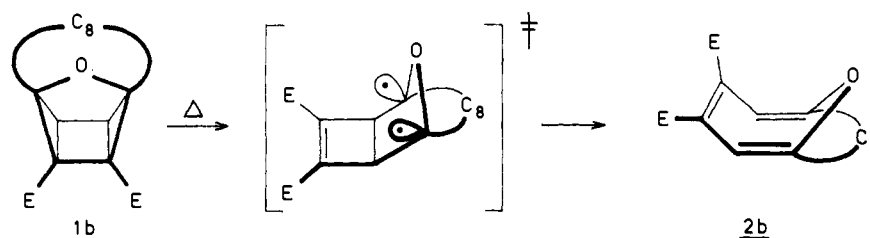
the structure of **3b** (Scheme VI). The structural characterization of **6b** (Scheme V) is based upon the following data: elemental analysis and mass number show that **6b** contains one oxygen atom less than the starting material **1b**; the ^1H NMR signals of the octamethylene chain hydrogens in **6b** are in part upfield shifted, if compared with those of **1b**, which agrees with the (1,4)cyclophane structure;³² the ^{13}C NMR spectrum of **6b** shows characteristic aromatic signals at δ 140.6 (s), 132.1 (s), and 132.8 (d, $J = 161$ Hz) and the UV spectrum of **6b** (96% $\text{C}_2\text{H}_5\text{OH}$) shows two bands at 217.5 nm (ϵ 22 100) and 301 (ϵ 1620).

The intermediates **10a**, **10b**, **10c**,³³ and **11b**³⁴ (Scheme VII) are characterized by ^{13}C and ^1H NMR spectroscopic data, obtained during the reactions of **1a**, **1b**, and **1c**, respectively, with AgClO_4 in C_6D_6 .³⁵ The following ^{13}C NMR spectroscopic data³⁶ are ascribed to the various intermediates: doublets at δ 139.7 ($J = 162$ Hz, C_3) and 137.0 ($J = 172$ Hz, C_4) and singlets at 82.4 (C_5) and 199.2 (C_6) to intermediate **10a**; doublets at δ 140.1 ($J \sim 160$ Hz, C_3) and 138.1 ($J \sim 170$ Hz, C_4) and singlets at 83.4 (C_5) and 199.2 (C_6) to intermediate **10b**; doublets at δ 131.8 ($J = 170$ Hz, C_4) and 68.8 ($J = 137$ Hz, C_5) and singlets at 134.8 (C_3) and 202.1 (C_6) to intermediate **11b**. Characteristic in the ^1H NMR spectra obtained from the reaction mixtures of **1a** and **1b** with AgClO_4 in C_6D_6 are AB-type absorptions which are ascribed to H_3 and H_4 in the structures of **10a** and **10b**, respectively. The centers of the doublets of the AB systems are observed at δ 6.40 and 6.05 ($J = 5.4$ Hz, **10a**) and 6.57 and 6.24 ($J = 5.6$ Hz, **10b**). If **1c** is used as starting material, an ABM-type absorption is observed, which is ascribed to H_2 , H_3 , and H_4 in the structure of **10c**. Multiplets are observed at δ 6.45 (1 H) and 6.12 (2 H). (No efforts have been made to determine the coupling constants.) This ABM system clearly indicates that the methyl substituent in **10c** is not bonded to the cyclopentadiene ring, for in that case one would expect an AB-type absorption as is the case in **10a** and **10b**.

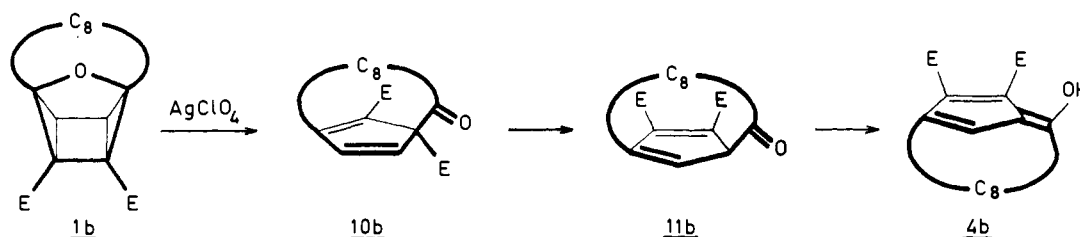
B. Reaction Mechanisms. 1. Thermal and Acid Catalyzed Reactions. In Table I it is shown that there exists a large difference in reaction rate between **1a** and **1b** in both the thermal decomposition and in the trichloroacetic acid catalyzed reaction, the ratio of rate constants being 165 and 125, respectively; however, in the transition metal catalyzed reactions the rates of **1a** and **1b** do differ much less. It is suggested that the difference in rates of the thermal decomposition is due to the energy difference of **1a** and **1b**—that of **1b** being higher, owing to a transannular effect in the 11-membered ring formed by the octamethylene chain and the rigid C-O-C fragment—being larger in the ground state than in the transition state,³⁷ as shown by Dreiding models (the reaction of **1b** is given in Scheme VIII).

In the case of the trichloroacetic acid catalyzed reactions of **1a** and **1b** an analogous explanation is thought to be valid for the observed rate difference between these compounds. The trichloroacetic acid catalyzed formation of **3a** and **3b** from **1a** and **1b**, respectively, rules out the possibility that the reaction of **1** with the acid proceeds via initial protonation of the ether oxygen atom,³⁸ obviously a reaction takes place between a trichloroacetic acid dimer³⁹ and a cyclopropyl ring of the oxaquadricyclane molecule. It is supposed that in this reaction

Scheme VIII

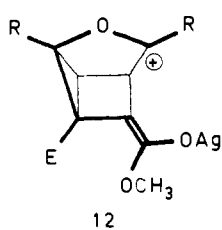


Scheme IX



a proton is transferred from the acid dimer to the oxaquadracyclane accompanied by a simultaneous proton transfer from the C_{β} atom of the oxaquadracyclane to the acid dimer.⁴⁰ Product **3a** formed in the trichloroacetic acid catalyzed reaction of **1a** in benzene is different from the product **4a**, which has been reported to be formed when a methylene chloride solution of **1a** is treated with sulfuric acid;¹⁹ this difference will obviously be due to the different reaction conditions. It is likely, however, that compound **3a** is also the initial product in the sulfuric acid catalyzed reaction of **1a** but that **3a** is not stable under the employed reaction conditions and is converted into **4a**.⁴¹

2. Silver Catalysis. As mentioned earlier, in case of the transition metal catalyzed reactions the rates of **1a** and **1b** are of the same magnitude. This may be explained by assuming that either the contribution of the transannular effect in **1b**, as mentioned above, will be about equal in the ground state and in the transition state or that the transition metal catalyzed reactions of **1b** are sterically hindered. The reactions of **1** with AgClO_4 are most interesting because in both benzene and methanol solution the 6-hydroxyfulvene derivatives **4** are the products formed.⁴² Structure **12**, proposed by Nelson et al.,⁴³

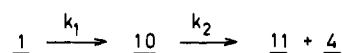


can be rejected as an intermediate on basis of the results obtained by Prinzbach and coworkers⁴⁴ for the analogous AgBF_4 catalyzed reaction of unsubstituted 3-oxaquadracyclane. To obtain more insight in the reaction of **1** with AgClO_4 (in benzene solution) the ^1H and ^{13}C NMR spectral changes were monitored during the course of the reactions. This has revealed that two intermediates, **10** and **11**, are formed in the reaction of **1** leading to **4** (in Scheme IX this is shown for the reaction of **1b**). Intermediates **10** are thermally not stable and rearrange to **11** by a 1,5 sigmatropic shift of the acyl fragment.⁴⁵ The 1,5 sigmatropic shift to **11** is followed by a keto-enol tautomerization of **11** to **4**.

The reactions of **1a** and **1b** with AgClO_4 in benzene have been subjected to a kinetic analysis.⁴⁶ The concentrations of **1**, **10**, and the sum of **11** + **4** have been monitored during the reactions by ^1H NMR spectroscopy. The results are given in Figure 1. If one considers the formation of **11** + **4** from **1** as the

result of two consecutive pseudo-first-order reactions (Scheme X), k_1 can be deduced from the slope of the straight line which

Scheme X



is obtained if $\ln [1]$ is plotted vs. time. This has been done for both **1a** and **1b**, the values being $7.5 \times 10^{-4} \text{ s}^{-1}$ and $3.8 \times 10^{-4} \text{ s}^{-1}$, respectively. When **[10]** has reached its maximum ($d[\underline{10}]/dt \equiv 0$)

$$d[\underline{10}]/dt = k_1[\underline{1}] - k_2[\underline{10}] \quad (1)$$

becomes

$$k_1[\underline{1}] = k_2[\underline{10}] \quad (\text{at } t([\underline{10}] = \text{max})) \quad (2)$$

from which k_2 can be calculated, using the values of **[1]** and of **[10]** at $t([\underline{10}] = \text{max})$ from Figure 1. In this way the value of k_2 can be calculated being $3.6 \times 10^{-4} \text{ s}^{-1}$ for **1a** and $22.7 \times 10^{-4} \text{ s}^{-1}$ for **1b**. The validity of the chosen model can be tested by substituting the calculated values for k_1 and k_2 in eq 3 (calculation of **[10]**) and eq 4 (calculation of **[11]** + **[4]**):

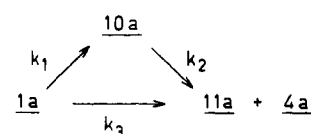
$$[\underline{10}] = \frac{k_1[\underline{1}]_{t=0}}{k_2 - k_1} (e^{-k_1 t} - e^{-k_2 t}) \quad (3)$$

(**[11]** + **[4]**)

$$= [\underline{1}]_{t=0} \left[1 + \frac{1}{k_1 - k_2} (k_2 e^{-k_1 t} - k_1 e^{-k_2 t}) \right] \quad (4)$$

The results of these calculations are given in Figure 2 and Figure 3. As one can see from Figure 2 the assumed model of a set of two consecutive pseudo-first-order reactions fits well for the reaction of **1b**. However, the same model does not fit for the reaction of **1a** (see Figure 3). In order to get a better correlation between experimental and calculated curves in case of **1a**, another kinetic model has been used allowing for a direct conversion of **1a** into **11a** + **4a** (Scheme XI). Equations 3 and

Scheme XI



4 then become eq 5 and 6, respectively:

$$[\underline{10a}] = \frac{k_1[\underline{1a}]_{t=0}}{k_2 - (k_1 + k_3)} (e^{-(k_1+k_3)t} - e^{-k_2 t}) \quad (5)$$

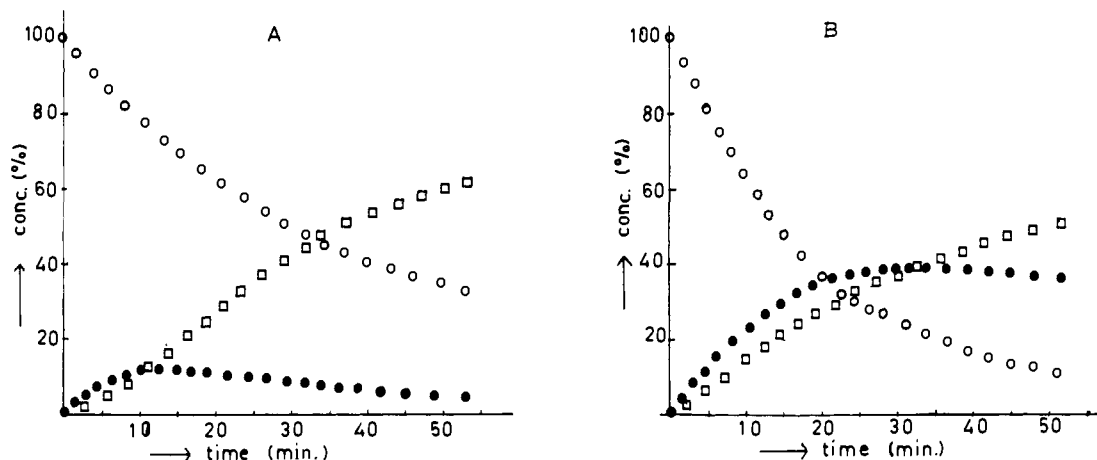


Figure 1. Silver perchlorate (0.03 M) catalyzed reactions of **1a** (B) and of **1b** (A) (0.3 M) in benzene: O, concentrations of **1a** or **1b**; ●, concentrations of **10a** or **10b**; □, concentrations of **11a + 4a** or **11b + 4b**.

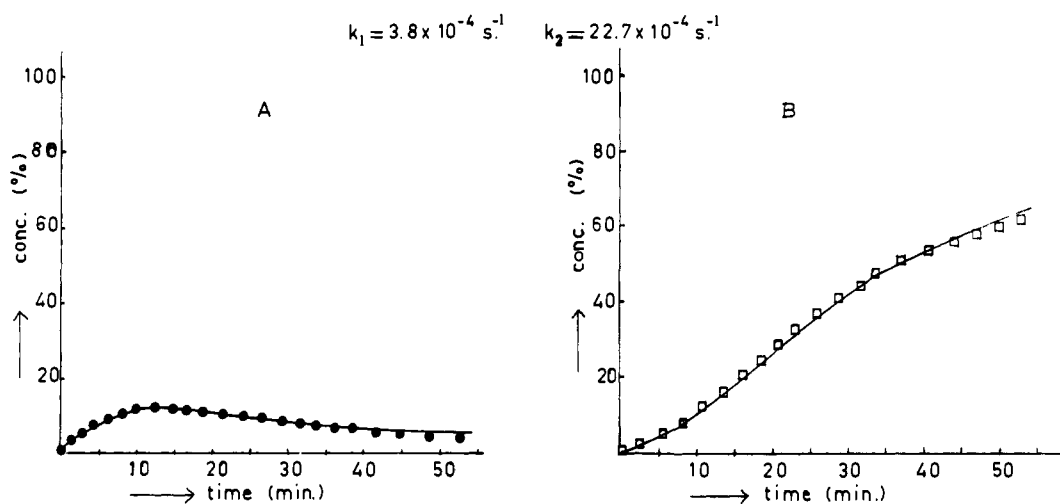


Figure 2. Experimental (●, □) and calculated (—) curves for the concentrations of **10b** (A) and of **11b + 4b** (B) vs. time, using the kinetic model in Scheme X.

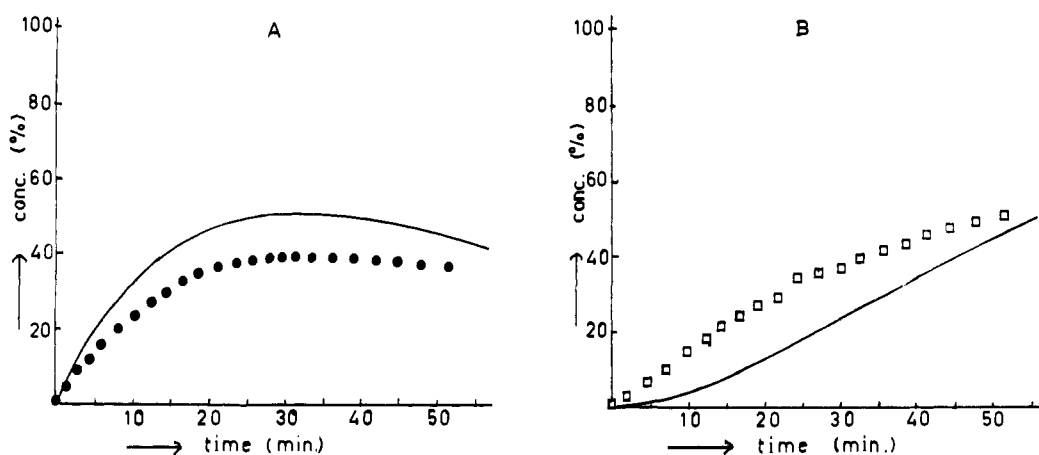


Figure 3. Demonstration of the bad correlation between the experimental (●, □) and calculated (—) curves for the concentrations of **10a** (A) and of **11a + 4a** (B) vs. time, using the kinetic model in Scheme X; k_1 being $7.5 \times 10^{-4} \text{ s}^{-1}$ and k_2 being $3.6 \times 10^{-4} \text{ s}^{-1}$.

$$([\mathbf{11a}] + [\mathbf{4a}]) = [\mathbf{1a}]_{t=0} \left[1 + \frac{1}{k_1 + k_3 - k_2} \times (k_2 - k_3)e^{-(k_1+k_3)t} - k_1e^{-k_2t} \right] \quad (6)$$

Because $d[\mathbf{10a}]/dt \approx 0$ when $[\mathbf{10a}]$ is at its maximum, eq 7 can be derived from eq 2 and 5 ($[\mathbf{1}] = [\mathbf{1}]_{t=0}e^{-(k_1+k_3)t}$):

$$k_2e^{-k_2t} = (k_1 + k_3)e^{-(k_1+k_3)t} \quad (\text{at } t([\mathbf{10a}] = \text{max})) \quad (7)$$

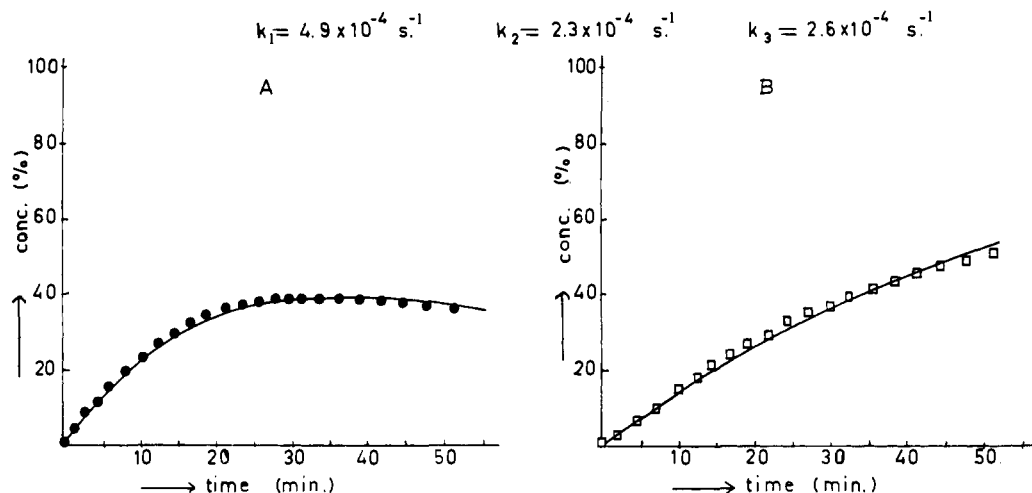


Figure 4. Experimental (●, □) and calculated (—) curves for the concentrations of **10a** (A) and of **11a** + **4a** (B) vs. time, using the kinetic model in Scheme XI.

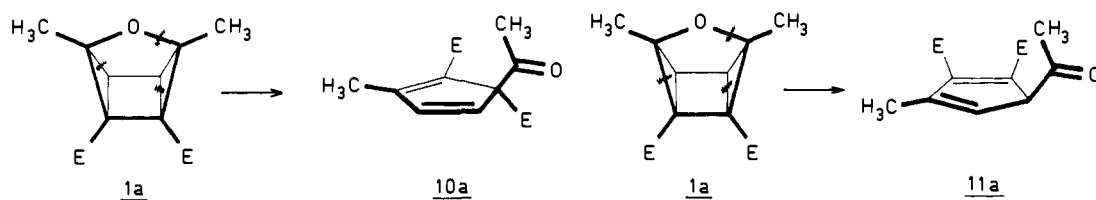
By substituting the values for $t([\mathbf{10a}] = \max)$ (obtained from Figure 1A) and $k_1 + k_3$ (the slope of the straight line, obtained by plotting $\ln [\mathbf{1a}]$ vs. time) in eq 7, k_2 has been calculated to be $2.3 \times 10^{-4} \text{ s}^{-1}$. From eq 2 k_1 is found to be $4.9 \times 10^{-4} \text{ s}^{-1}$ and consequently k_3 is $(7.5 \times 10^{-4} - 4.9 \times 10^{-4}) = 2.6 \times 10^{-4} \text{ s}^{-1}$. This kinetic model describes the Ag(I) catalyzed reaction of **1a** correctly as can be judged by a comparison of experimental and calculated (applying eq 5 and 6) values for the concentration of **10a** and **11a** + **4a** (Figure 4).

Comparison of the rate constants for the reactions of **1a** and **1b** reveals that the values for k_1 are almost the same ($4.9 \times 10^{-4} \text{ s}^{-1}$ and $3.8 \times 10^{-4} \text{ s}^{-1}$, respectively). The difference of a factor of 10 in the k_2 values ($k_2(\mathbf{1a}) = 2.3 \times 10^{-4} \text{ s}^{-1}$, and $k_2(\mathbf{1b}) = 22.7 \times 10^{-4} \text{ s}^{-1}$) is likely to be due to **10b** being less stable than **10a** as a result of a steric repulsion, as indicated by molecular models, between the octamethylene chain and the ester substituent at the olefinic carbon atom in **10b**. The remarkable difference between the kinetic behavior of the silver catalyzed reactions of **1a** and **1b** is the direct formation of **11a** from **1a**, whereas **11b** is not directly formed from **1b**.⁴⁷ What

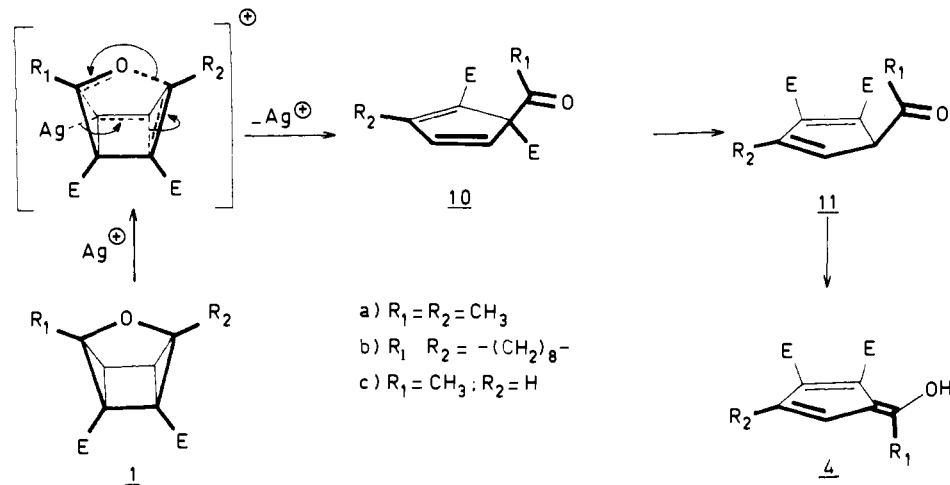
may be the reason for this different behavior? Compounds **1a** and **1b** differ from each other by the bridgehead substituents: two methyl groups in **1a** and an octamethylene chain in **1b**. In the latter case reactions at the C-O-C fragment may be hindered or even prohibited as a consequence of the presence of the octamethylene chain. Therefore it is supposed that the direct formation of **11** from **1**, which is observed in the case of **1a** and not of **1b**, is the result of an attack of Ag(I) on the C-O-C fragment⁴⁹ (vide infra, Scheme XIV).

In Scheme XII it is indicated what bonds in **1a** must be broken to produce **10a** and **11a**, respectively, the difference being one of the two cyclopropyl bonds which are broken. From the evidence that compounds **10a** and **11a** are formed from **1a** via different routes and that the direct formation of **11a** from **1a** occurs via an attack of Ag(I) on the C-O-C fragment, it is reasonable to conclude that, for the formation of **10a** from **1a** (and also **10b** from **1b**), Ag(I) will not attack the C-O-C fragment but rather one of the bonds of a cyclopropyl ring. In view of the difference in inductive effects of a methyl and of an ester substituent,⁵⁰ the most probable bond to be attacked

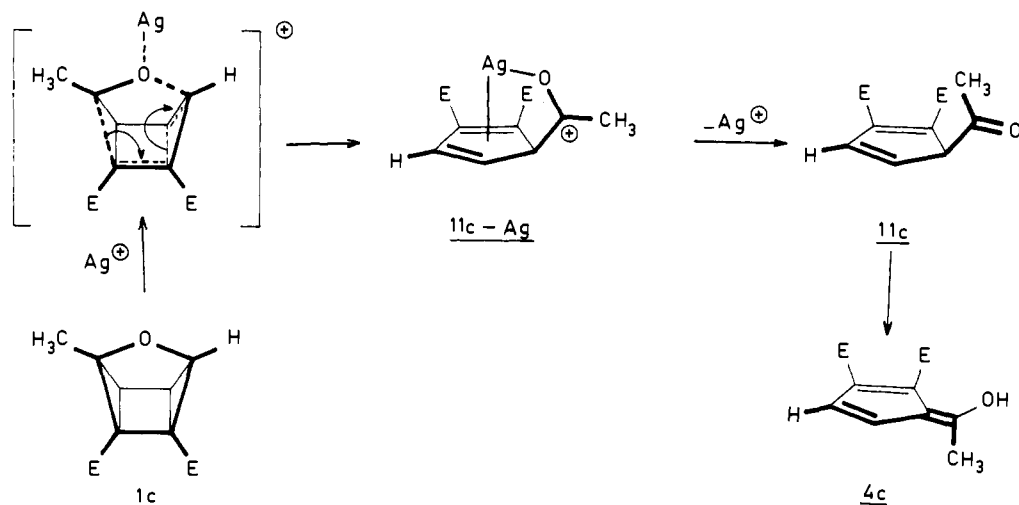
Scheme XII



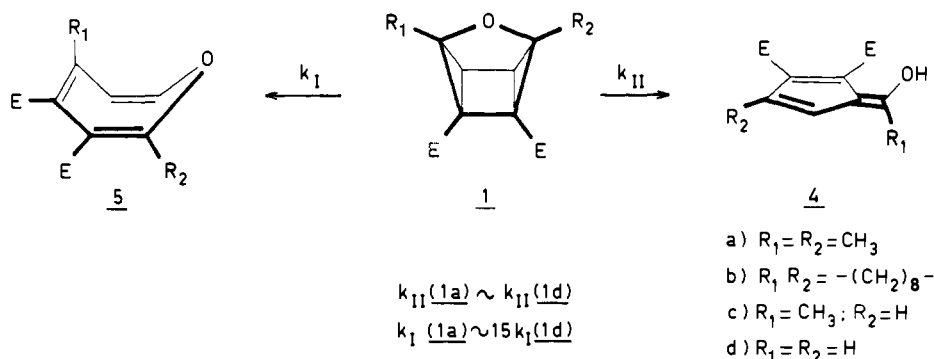
Scheme XIII



Scheme XIV



Scheme XV



is the one with the methyl substituent (Scheme XII). Consistent with this mechanistic picture is the exclusive formation of 4c (via 10c and 11c) from 1c.⁵¹ In Scheme XIII the mechanism of the Ag(I) catalyzed reaction of 1, proceeding at a cyclopropyl ring is given.

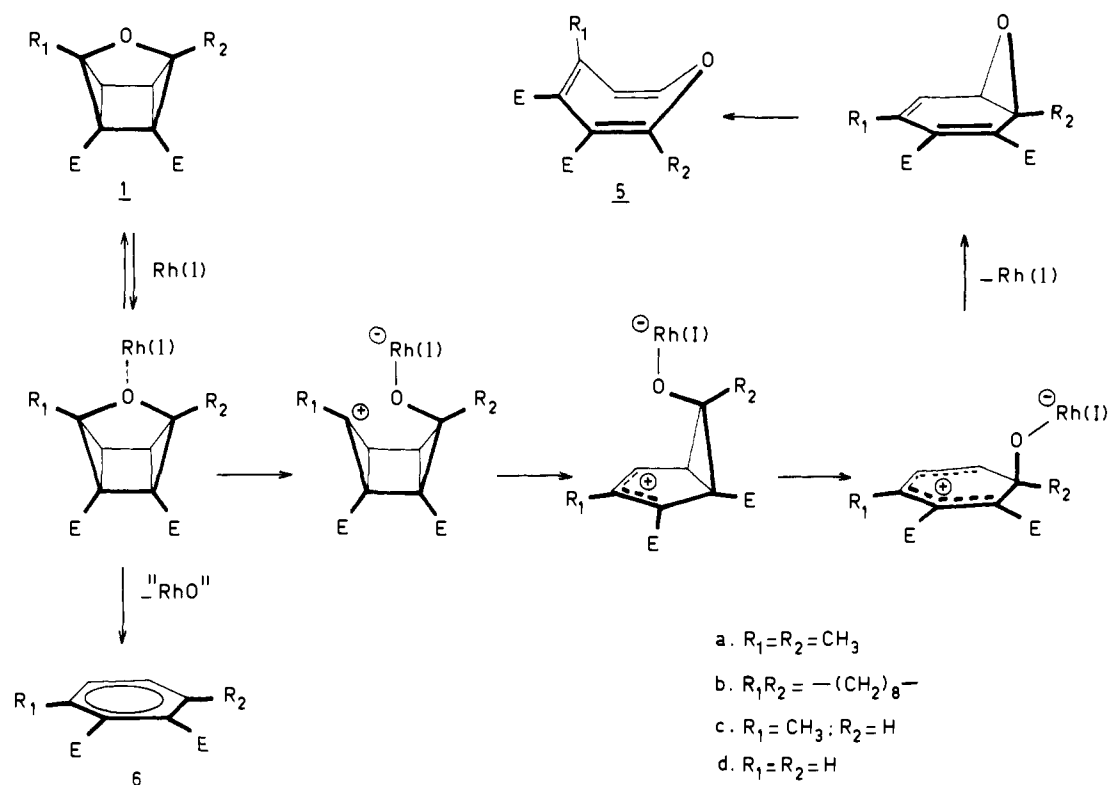
Compound 11c is also formed directly from 1c, analogously to 11a from 1a, via an attack of Ag(I) on the C-O-C fragment. The exclusive formation of 11c shows that in this process the O-C(H) bond—and not the O-C(CH₃) bond, which would have led to 11 (R₁ = H; R₂ = CH₃)—is exclusively broken. This is surprising in view of the inductive effect of the methyl substituent;^{50,52} it probably indicates that the transition state of the process 1c → 11c is quite close to a structure like 11c-Ag, which is more stabilized by the methyl substituent than the corresponding isomeric structure in which CH₃ and H have been interchanged. The mechanism of the Ag(I) catalyzed reaction of 1c, proceeding at the C-O-C fragment, is summarized in Scheme XIV. (This mechanism can also be applied for the analogous process of 1a.⁵³)

3. Rhodium and Palladium Catalysis. Inspection of Scheme V reveals that the reactions of 1a and 1b with Rh₂(CO)₄Cl₂ in benzene solution lead to different main products: 1a affords 5a and 1b affords 6b. This difference in product formation is unlikely to be due to an initially formed compound 5b (Scheme XV) being unstable under the employed conditions and being converted into 6b;⁵⁴ it is more probable that the octamethylene chain does not allow for the formation of 5b because of a considerable strain brought about by the octamethylene chain (vide infra).

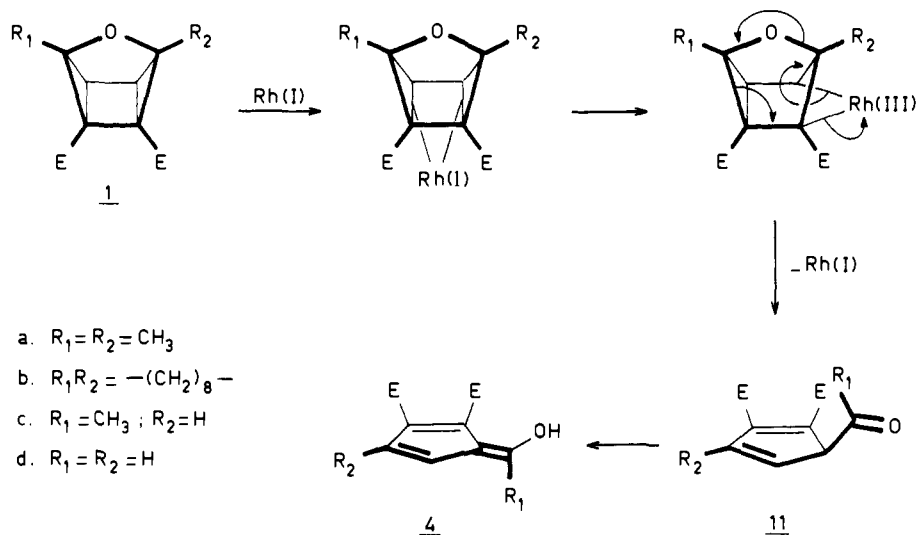
As far as the formation of 6-hydroxyfulvenes 4 from 1 is concerned, the intriguing question arises whether the formation of those compounds is the result of some proton catalyzed process, as suggested by Vogel,²¹ or of some rhodium catalyzed process. It seems difficult for us to accept the former interpretation because of the following reasons: (a) reactions of 1a

and of 1b with CCl₃COOH in benzene do not lead to 4a and 4b, but instead to 3a and 3b (see above); (b) compound 4b is not formed from 3b by Rh₂(CO)₄Cl₂ in benzene solution after 2 days at room temperature (so 3b cannot be an intermediate in the conversion 1b → 4b), whereas the formation of 4b from 1b in methylene chloride solution by concentrated sulfuric acid most probably proceeds via 3b (see note 41); (c) in the Rh₂(CO)₄Cl₂ catalyzed reaction of 1b, both 3b and 4b are formed in contrast to the CCl₃COOH catalyzed reaction which only affords 3b (see above). To obtain further indications that the formation of 6-hydroxyfulvenes are rhodium catalyzed reaction products, we have compared the reactions of 1a and 1d. This has revealed that, on basis of the amounts of products formed after 25 and 50% conversion of 1a and 1d, the formation of 6-hydroxyfulvenes 4a and 4d occurs at about the same rate, whereas the rate of formation of the oxepine 5a is at least 15 times faster than that of 5d would be.⁵⁸ This suggests that, starting from 1, two routes can be followed: one leading to oxepines 5, the other to 6-hydroxyfulvenes 4⁵⁹ (Scheme XV). Moreover, it is tempting to conclude that—in view of the effect of the methyl groups—in the former route the rate-determining step involves an intermediate with carbonium-ion character, whereas this is unlikely in the latter one.⁶⁰ The formation of the oxepines 5 is likely to be due to the action of Rh₂(CO)₄Cl₂ as a Lewis acid,⁶¹ attacking the ether oxygen atom of the C-O-C fragment. Subsequent cleavage of a C-O bond and opening of a cyclopropyl ring will yield a bicyclic intermediate with carbonium-ion character. Opening of the central bond of the bicyclo[3.1.0]hexenyl cation can afford the corresponding cyclohexadienyl cation,⁶² which—on losing Rh(I)—is converted into the benzene oxide isomer of 5⁶³ (Scheme XVI). From Scheme XVI it can be seen that another reaction—initiating too at the ether oxygen atom of the C-O-C fragment, passing through a same intermediate and leading to the deoxygenated compounds 6 by losing “RhO”—competes

Scheme XVI



Scheme XVII



with the one in which compounds **5** are formed. From inspection of molecular models it may become clear why compound **5b** is not formed in the reaction of **1b** catalyzed by $\text{Rh}_2(\text{CO})_4\text{Cl}_2$: a Dreiding model of the bicyclo[3.1.0]hexenyl cation derived from **1b** (Scheme XVI) shows that such a species is very unlikely to be formed, because of the large amount of strain introduced by the octamethylene chain.⁶⁴ As a result the competing reaction occurs, leading to **6b** on losing "RhO". Scheme XVI also may account for the lack of formation of **5d** in the reaction of **1d** with $\text{Rh}_2(\text{CO})_4\text{Cl}_2$: a secondary cyclopropyl cation would be involved which is less stable and will be formed (much) slower⁴⁸ than the corresponding tertiary cyclopropyl cation derived from **1a**. As a result it might be likely that the competing reaction—leading to **6d**—is favored.

The formation of 6-hydroxyfulvenes **4** from **1** by $\text{Rh}_2(\text{CO})_4\text{Cl}_2$ is proposed to occur as follows:^{65,66} the CO ligands

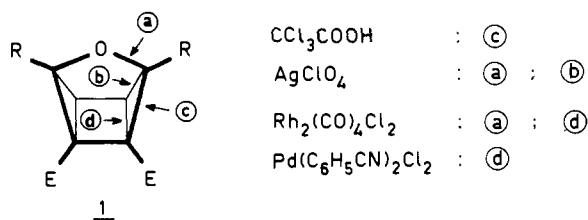
in the starting complex are replaced by (an) oxaquadricyclane molecule(s), subsequent oxidative addition⁶⁷ of a cyclopropyl ring to the metal occurs, and finally the complex decomposes liberating the keto tautomer of the 6-hydroxyfulvenes⁶⁸ (Scheme XVII).

Finally, the $\text{Pd}(\text{C}_6\text{H}_5\text{CN})_2\text{Cl}_2$ catalyzed reactions of **1** need some comment; as mentioned earlier the sole products being formed are compounds **4**. Like the $\text{Rh}_2(\text{CO})_4\text{Cl}_2$ catalyzed and unlike the AgClO_4 catalyzed reactions of **1a** the formation of **4a** is not proceeding via intermediate **10a**. This is not due to **10a** being unstable under the reaction conditions, for, if **10a** is generated in a separate experiment by the AgClO_4 catalyzed reaction of **1a** (followed by decomposition of the silver catalyst by excess NaI), it is not affected by the presence of $\text{Pd}(\text{C}_6\text{H}_5\text{CN})_2\text{Cl}_2$, added in a catalytic amount (10 mol %). In the Pd(II) catalyzed reaction of **1c** the O-C(H) bond is broken: there is exclusive formation of **4c**. The exclusive for-

mation of **4c** might be interpreted as follows: either Pd(II) reacts analogously to Ag(I), which implies that the reaction has to proceed exclusively via an attack on the C–O–C fragment (compare Scheme XIV), or an oxidative addition of a cyclopropyl ring to Pd(II) occurs analogously to Rh(I) (compare Scheme XVII). Although it is difficult to distinguish unambiguously between the two alternative interpretations, we prefer the latter one, because of the observation that in the Pd(II) catalyzed reaction of **1b** compound **4b** is formed, which is unlikely to be the result of an initial attack of the catalyst at the C–O–C fragment (compare the Ag(I) catalyzed reactions, see above).

Concluding Remarks⁶⁹

In Scheme XVIII the bonds of oxaquadracyclanes are shown which are cleaved initially by the various catalysts used. Kinetic Scheme XVIII



evidence has been offered for the occurrence of two reaction paths (via the C–O–C fragment and a cyclopropyl ring) in the AgClO_4 catalyzed reactions, both leading to 6-hydroxyfulvenes. The formation of 6-hydroxyfulvenes in the $\text{Pd}(\text{C}_6\text{H}_5\text{CN})_2\text{Cl}_2$ and $\text{Rh}_2(\text{CO})_4\text{Cl}_2$ catalyzed reactions has been attributed to a process involving an oxidative addition of oxaquadracyclane to the metal, and proceeding via intermediates showing no carbonium-ion character. However, $\text{Rh}_2(\text{CO})_4\text{Cl}_2$ also reacts as a Lewis acid; in those processes the reactions involve intermediates with carbonium-ion character and lead to the formation of oxepine derivatives; a competing reaction affords the corresponding deoxygenated products (i.e., aromatic compounds). The formation of 6-hydroxyfulvenes in the metal catalyzed reactions are shown to be due to metal—and not to acid catalysis. It has been established that the CCl_3COOH catalyzed reactions lead to the cleavage of one cyclopropyl bond in the oxaquadracyclane substrates. Finally it was shown that the octamethylene chain in **1b** has an appreciable influence on the course of the reactions with AgClO_4 and $\text{Rh}_2(\text{CO})_4\text{Cl}_2$.

Experimental Section

Materials and Apparatus. All glassware used in the catalyzed reactions were washed with 10% NH_4OH solution and dried at 140 °C prior to use. Solvents were purified as follows:⁷⁰ ether was distilled from P_2O_5 followed by distillation from LiAlH_4 and stored over sodium wire; benzene was distilled and dried for 2 days over anhydrous CaCl_2 and subsequently over sodium; (m)ethanol was distilled from magnesium and stored over molecular sieves. The starting materials cyclododecanone and dicarbomethoxyacetylene were purchased from E.G.A.-Chemie K.G. and furan, 2-methylfuran, and 2,5-dimethylfuran from Aldrich—Europe. Melting points are uncorrected and were recorded on a Reichert apparatus, with microscope equipment. ¹³C and ¹H NMR (100 MHz) spectra were recorded on a Varian XL-100 and 60-MHz ¹H NMR spectra on a Varian A-60D or a JEOL C-60 HL high resolution spectrometer; UV spectra were recorded on a Zeiss PMQ II spectrophotometer. Mass spectra were recorded by A. Kiewiet on a AEI MS902 apparatus. Elemental analyses were performed by H. Draayer, J. Ebels, J. Hommes, and J. E. Vos of the analytical section of the department. Compounds **1a**, **1c**, and **1d** were prepared according to literature procedures.^{13b}

[8](2,4)-1,5-Dicarbomethoxy-3-oxaquadracyclane (1b). The preparation of [8](2,5)furanophane was accomplished by using the procedures described in the literature.⁷¹ [8](2,5)Furanophane (6.2 g, 35 mmol) and dicarbomethoxyacetylene (4.86 g, 34 mmol) were heated

at 70 °C for 24 h. The crude Diels–Alder adduct was purified by column chromatography (Al_2O_3 , Merck No. 1097; CH_2Cl_2) and was obtained as a slightly yellow viscous oil: yield 9.5 g (30 mmol, 88%); ¹H NMR (CDCl_3) δ 6.97 (s, 2 H), 3.78 (s, 6 H), 1.97–2.33 (m, 4 H), 1.13–1.78 (m, 12 H). The Diels–Alder adduct (2.1 g, 7 mmol) was dissolved in 125 mL of ether and the solution was irradiated at –40 °C in a N_2 atmosphere (Hanau S81, high pressure, Pyrex filter). After 3 h >95% of the starting material had been converted. The ether solution was washed with 10% KOH solution and after drying the ether was evaporated, leaving a pale yellow solid. Several crystallizations from *n*-hexane afforded **1b** as colorless crystals: yield 1.4 g (4.8 mmol, 68%); mp 59–60 °C; mass spectrum parent peak at *m/e* 320; ¹H NMR (CDCl_3) δ 3.70 (s, 6 H), 2.63 (s, 2 H), 1.83–2.19 (m, 4 H), 1.38–1.83 (m, 8 H), 0.99–1.38 (m, 4 H). Anal. Calcd for $\text{C}_{18}\text{H}_{24}\text{O}_5$: C, 67.48; H, 7.56; O, 24.97. Found: C, 67.53; H, 7.66; O, 25.20.

[8](2,7)-4,5-Dicarbomethoxyoxepine (2b). **1b** (100 mg, 0.3 mmol) was dissolved in 1 mL of benzene and the solution was heated for 24 h at 60 °C. According to ¹H NMR spectroscopy quantitative conversion to **2b** had occurred. After removal of the solvent the oxepine was obtained as an orange oil. It was purified by sublimation (85–90 °C at 0.05 mmHg) to give yellow crystals: yield 79 mg (0.24 mmol, 80%); mp 69–70 °C; ¹H NMR (CDCl_3) δ 5.52 (br s, 2 H), 3.75 (s, 6 H), 2.14–2.55 (m, 4 H), 1.25–1.75 (m, 12 H). Anal. Calcd for $\text{C}_{18}\text{H}_{24}\text{O}_5$: C, 67.48; H, 7.56; O, 24.97. Found: C, 67.32; H, 7.51; O, 25.30.

Reactions of 1a and 1b with CCl_3COOH in Benzene. **1b** (320 mg, 1.0 mmol) was dissolved in 3 mL of benzene and 16.4 mg (0.1 mmol) of CCl_3COOH was added. After 3 min at room temperature **1b** had disappeared completely according to ¹H NMR spectroscopy. Chloroform (5 mL) was added and the solution washed with water. After drying and removal of the solvent, **3b** was obtained as a colorless solid, which was crystallized from petroleum ether (60–80 °C): yield 285 mg (0.9 mmol, 90%); mp 145–146 °C; mass spectrum parent peak at *m/e* 320; ¹H NMR (CDCl_3) δ 4.30 (dd, 1 H, *J* = 7 and 6.5 Hz), 3.78 (d, 1 H, *J* = 8 Hz), 3.70 (s, 3 H), 3.65 (s, 3 H), 3.27 (dd, 1 H, *J* = 3.5 and 8 Hz), 3.03 (d, 1 H, *J* = 3.5 Hz), 0.83–2.77 (m, 14 H); ¹³C NMR (CDCl_3)^{72a} δ 170.12 (s), 169.01 (s), 156.49 (s), 97.78 (d, *J* = 162 Hz), 81.16 (s), 51.75 (q, *J* = 148 Hz), 51.47 (q, *J* = 148 Hz), 42.52 (d, *J* = 143 Hz), 41.53 (d, *J* = 157 Hz), 36.96 (d, *J* = 193 Hz), 36.56 (s). Anal. Calcd for $\text{C}_{18}\text{H}_{24}\text{O}_5$: C, 67.48; H, 7.56; O, 24.97. Found: C, 67.47; H, 7.50; O, 25.07. The reaction of **1a** was carried out for comparison and performed on a small scale. **1a** (36 mg, 0.15 mmol) was dissolved in 0.5 mL of C_6D_6 containing 2.5 mg (0.015 mmol) of CCl_3COOH . After 1 h at room temperature, 50% of **1a** had been converted; after standing overnight **1a** had disappeared completely and 75–80% of **3a** had been formed according to ¹H NMR spectroscopy (C_6D_6): δ 4.26 (d, 1 H, *J* = 1.5 Hz), 3.78 (d, 1 H, *J* = 1.5 Hz), 3.56 (d, 1 H, *J* = 8.3 Hz), 3.35 (s, 3 H), 3.29 (s, 3 H), 2.79 (dd, 1 H, *J* = 8.3 and 3.3 Hz), 2.36 (d, 1 H, *J* = 3.3 Hz), 1.84 (s, 3 H).

General Procedure for the Reactions of 1 with AgClO_4 in Benzene. AgClO_4 was dried for 1 h at 120 °C in vacuo prior to use. The reactions were carried out in C_6D_6 solution with NMR spectroscopic quantities. Products were not isolated but characterized by comparing the ¹H NMR spectra with those of authentic material.^{12,73} Yields were estimated by integration of the ¹H NMR peaks relative to an internal standard. **1** (0.15 mmol) was dissolved in 0.5 mL of C_6D_6 containing 3.1 mg (0.015 mmol) of AgClO_4 . The reactions were followed by ¹H NMR spectroscopy at 27 °C and by ¹³C NMR spectroscopy at 18 °C.

Compound 10a: ¹H NMR (C_6D_6) δ 6.40 (d, 1 H, *J* = 5.5 Hz), 6.05 (d, 1 H, *J* = 5.5 Hz), 3.47 (s, 3 H), 3.34 (s, 3 H), 2.02 (s, 3 H), 1.69 (s, 3 H); ¹³C NMR^{72b} (C_6D_6) δ 199.19 (s), 166.41 (s), 164.12 (s), 156.89 (s), 139.72 (d, *J* = 161 Hz), 136.95 (d, *J* = 161 Hz), 82.34 (s), 52.33 (q, *J* = 147 Hz), 51.13 (q, *J* = 147 Hz), 23.62 (q, *J* = 128 Hz), 14.92 (q, *J* = 130 Hz).

10b: ¹H NMR^{72c} (C_6D_6) δ 6.57 (d, 1 H, *J* = 5.7 Hz), 6.24 (d, 1 H, *J* = 5.7 Hz), 3.61 (s, 3 H), 3.48 (s, 3 H); ¹³C NMR^{72d,e} (C_6D_6) δ 199.19 (s), 165.78 (s), 164.70 (s), 140.14 (d, *J* ~ 160 Hz), 138.10 (d, *J* ~ 170 Hz), 52.29 (q, *J* = 148 Hz), 51.05 (q, *J* = 148 Hz).

10c: ¹H NMR (C_6D_6) δ 6.45 (m, 1 H), 6.12 (m, 2 H), 3.60 (s, 3 H), 3.48 (s, 3 H), 1.97 (s, 3 H).

11b: ¹H NMR^{72f} (C_6D_6) δ 5.74 (m, 1 H), 4.33 (m, 1 H), 3.68 (s, 3 H), 3.41 (s, 3 H); ¹³C NMR (C_6D_6)^{72g} δ 202.09 (s), 163.59 (s), 162.52 (s), 152.09 (s), 148.92 (s), 134.76 (s), 131.82 (d, *J* ~ 170 Hz), 68.78 (d, *J* = 138 Hz), 52.14 (q, *J* = 147 Hz), 51.51 (q, *J* = 147 Hz).

General Description of the Kinetic Runs for the Silver(I) Catalyzed Rearrangements of 1a and 1b. Solutions of **1** (0.15 mmol) in C₆D₆ (0.5 mL) containing AgClO₄ (0.015 mmol) were prepared at 0–5 °C; the conversions were monitored by measuring the concentrations of **1**, **10**, and **11** + **4** by integration of suitable ¹H NMR signals of these compounds at appropriate intervals at 27 °C, until 90% of **1a** and 70% of **1b**, respectively, had been converted. The measured values were plotted in Figure 1. The pseudo-first-order rate constants for the conversions of **1** were obtained by plotting ln [1] vs. time (least-squares method).

Effect of Na₂CO₃ on a Solution of AgClO₄ in Benzene. To 5 mL of a 0.026 M solution of AgClO₄ in benzene was added an excess of solid Na₂CO₃ (0.14 g, 1.3 mmol). After very efficient mechanical stirring for ~40 min, the solution was filtered (leaving a pale yellow solid). The filtrate was analyzed for silver (A.A.S. method) showing that no silver was left in the solution.

General Procedure for the Reactions of 1 with Pd(C₆H₅CN)₂Cl₂ in Benzene. The reactions were carried out in C₆D₆ solution. Products were characterized by comparing the ¹H NMR spectra of the reaction products with those of authentic samples of compounds **4**;^{12,73} they have not been isolated. Yields were estimated by integration of appropriate signals relative to an internal standard. **1** (0.15 mmol) was dissolved in 0.5 mL of C₆D₆; 5.7 mg (0.015 mmol) of Pd(C₆H₅CN)₂Cl₂ and 50 mg of NaHCO₃ were added. Reactions were carried out at room temperature.

Reaction of 1b with Rh₂(CO)₄Cl₂ in Benzene. **1b** (320 mg, 1.0 mmol) was dissolved in 3 mL of benzene followed by addition of 38.9 mg (0.1 mmol) of Rh₂(CO)₄Cl₂. After the solution was heated at 45 °C in a nitrogen atmosphere for 1 h, **1b** had disappeared completely. The reaction products were isolated by thin-layer chromatography (SiO₂, CH₂Cl₂) to yield five fractions. The first fraction contained compounds **6b** and **7b**, which were further separated on a SiO₂ thin layer by repeatedly eluting with benzene. Both **6b** and **7b** were crystallized from *n*-hexane and isolated as colorless crystals.

6b: yield 106 mg (0.35 mmol, 35%); mp 52–53 °C; mass spectrum: parent peak at *m/e* 304; ¹H NMR (CDCl₃) δ 7.23 (s, 2 H), 3.83 (s, 6 H), 2.90–3.37 (m, 2 H), 2.20–2.73 (m, 2 H), 0.05–1.85 (m, 12 H); ¹³C NMR (CDCl₃) δ 168.33 (s), 140.56 (s), 132.76 (d, *J* = 161 Hz), 132.06 (s), 52.17 (q, *J* = 147 Hz), 33.79 (t, *J* = 126 Hz), 30.26 (t, *J* = 130 Hz), 29.16 (t, *J* = 135 Hz), 25.33 (t, *J* = 126 Hz); UV (96% C₂H₅OH) 217.5 nm (ε 22 100), 301 (1620). Anal. Calcd for C₁₈H₂₄O₄: C, 71.03; H, 7.95; O, 21.02. Found: C, 70.76; H, 8.00; O, 20.98.

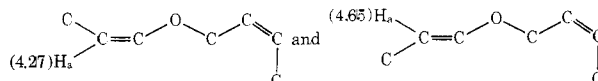
7b: yield 32 mg (0.1 mmol, 10%); mp 54–55 °C; mass spectrum: parent peak at *m/e* 320; ¹H NMR (CCl₄) δ 10.75 (s, 1 H), 7.35 (br s, 1 H), 3.87 (br s, 3 H), 3.76 (br s, 3 H), 2.37–2.93 (m, 4 H), 0.73–1.95 (m, 12 H); UV (*n*-hexane) 209 nm (ε 13 650), 252 (3200), 329 (2390).

The second fraction contained compounds **2b** (yield 15 mg, 0.05 mmol, 5%) and **4b** (yield 31 mg, 0.1 mmol, 10%); yields were estimated by ¹H NMR spectroscopy. The third fraction (yield 15 mg) and the fifth fraction (yield 30 mg) contained unidentified compounds; the fourth fraction consisted of compound **3b** (yield 32 mg, 0.1 mmol, 10%).

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References and Notes

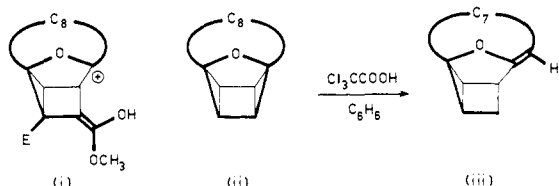
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- Reactions of **1** with Rh₂(norbornadiene)₂Cl₂ have also been carried out. The results obtained are analogous to those of the reactions of **1** with Pd(C₆H₅CN)₂Cl₂.
- The reactions of **1a** with Rh₂(CO)₄Cl₂ and AgBF₄ and the thermal decomposition of **1a** have already been described in the literature; see ref 21, 20, and 13a, respectively. We have confirmed the reported results.
- An acidic medium is also generated when bicyclobutane derivatives are treated with Pd(C₆H₅CN)₂Cl₂ in methanol solution, caused by an interaction between catalyst, product, and methanol; see ref 18d. In the case at hand one can imagine that the catalyst reacts with already formed 6-hydroxyfulvene; this reaction may very well cause the formation of a small amount of HCl, which in turn causes the fast acid catalyzed reaction of **1b** (Table I).
- The reactions of **1a** and **1b** with AgClO₄ in methanol lead to precipitation of Ag(0), in contrast to those in benzene solution. We do not believe that the formation of **4a** and **4b** from **1a** and **1b**, respectively, does involve redox processes of the type recently proposed to occur in the reaction of quadricyclane, promoted by silver trifluoroacetate: G. F. Koser and J. N. Faircloth, *J. Org. Chem.*, **41**, 583 (1976). The reason of the formation of Ag(0) may be the decomposition in methanol of intermediate cyclopentadiene-silver complexes. Compare for instance the fact that cyclopentadiene-silver tetrafluoroborate (C₅H₆AgBF₄) can only be prepared in aprotic and not in protic solvents (G. Stolze, Ph.D. Thesis, University of Munich, 1961). See also a review on organosilver chemistry: C. D. M. Beverwijk, G. J. M. van der Kerk, A. J. Leusink, and J. G. Noltes, *Organomet. Chem. Rev., Ser. A*, **5**, 215 (1970). The assumption that cyclopentadiene-silver complexes may be intermediates in the reaction of **1** with AgClO₄ is based upon the observation of intermediates **10** and **11**, both being cyclopentadiene derivatives (Scheme VII).
- The spectroscopic data are given in the Experimental Section.
- Compare for instance the values for the following compounds: CH₂=CHO-*n*-Bu, δ 107.8 (C_β), and *cis*-CH₃CH=CHO-*n*-Bu 93.5 (C_β) (T. Higashimura, S. Okamura, I. Morishima, and T. Yonezawa, *J. Polym. Sci., Part B, Polym. Lett.*, **7**, 23 (1969)).
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- Compare the reported ¹H NMR data of the following compounds:



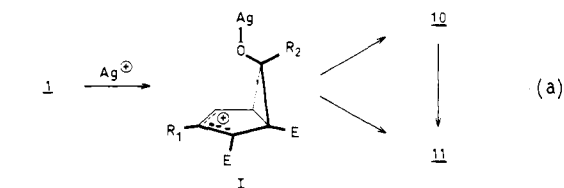
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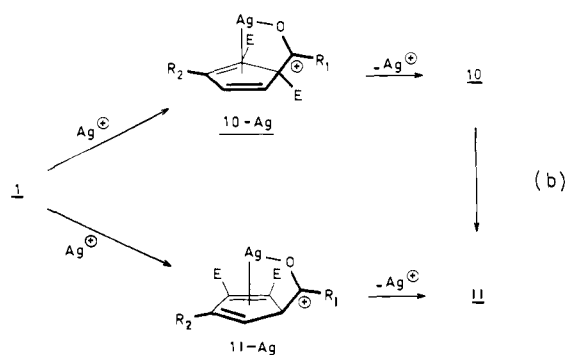
- (33) Intermediate **10c** has only been characterized by ^1H NMR spectroscopy, based upon analogy to **10a** and **10b**.
- (34) The intermediates **11a** and **11c** have not been observed in the NMR spectra, but they are assumed to be formed analogously to **11b**.
- (35) The structure of **10** is analogous to the reported reaction product of 1,5-dicarbomethoxy-3-isopropylidenequadricyclane with AgBF_4 in CH_2Cl_2 : S. F. Nelson, J. P. Gillespie, P. J. Hintz, and E. D. Seppanen, *J. Am. Chem. Soc.*, **95**, 8380 (1973).
- (36) For relevant analogous chemical shifts and coupling constants, see J. B. Stothers, " ^{13}C -NMR Spectroscopy", Academic Press, New York, N.Y., 1972.
- (37) W. Eberbach, M. Perroud-Arguelles, E. Druckrey, and H. Prinzbach, *Helv. Chim. Acta*, **54**, 2579 (1971).
- (38) The possibility of the proton attacking an ester carbonyl oxygen giving **i** is unlikely because of the fact that reaction of **ii** (prepared analogously to the method described by H. Prinzbach and H. Babsch, *Angew. Chem.*, **87**, 772 (1975)) with trichloroacetic acid leads to a similar product (**iii**); unpublished results.



- (39) (a) It is a well-known fact that in aprotic solvents carboxylic acids mainly occur as dimers; see for instance H. A. Goldman and M. F. Emerson, *J. Phys. Chem.*, **77**, 2295 (1973), and references cited therein. (b) The reaction of carboxylic acids with 1-ethoxyvinyl esters has been shown to involve dimers of the acid: B. Zwanenburg and W. Drenth, *Recl. Trav. Chim. Pays-Bas*, **82**, 862 (1963).
- (40) The fact that **3b** contains a trisubstituted and **3a** a disubstituted $\text{C}=\text{C}$ double bond constitutes another contribution to the observed difference in rate.
- (41) Unpublished results. Under the experimental conditions used by McCullough et al. (see ref 19), **1b** and **3b** afford exactly the same product mixture, containing ~30% **4b**.
- (42) The formation of **4** from **1** in the AgClO_4 catalyzed reactions is not due to an acid catalyzed process (the fact that, in the presence of solid Na_2CO_3 and otherwise the same conditions, no reaction occurs is due to the disappearance of $\text{Ag}(\text{I})$ from the solution; see Experimental Section) as shown by the following facts: (a) the reaction of **1b** with either CCl_3COOH in benzene or with a benzene solution pretreated with 70% HClO_4 leads to **3b**; (b) after 2 days at room temperature compound **3b** has not reacted with AgClO_4 .
- (43) S. F. Nelson and J. C. Calabrese, *J. Am. Chem. Soc.*, **95**, 8385 (1973).
- (44) Reaction of the unsubstituted 3-oxaquadricyclane with AgBF_4 in benzene leads to the corresponding 5-formylcyclopentadiene: H. Prinzbach and H. Babsch, *Angew. Chem.*, **87**, 772 (1975).
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- (46) For details see A. A. Frost and R. G. Pearson, "Kinetics and Mechanisms", Wiley, New York, N.Y., 1953, p 153.
- (47) Alternative explanations consistent with the kinetic behavior of **1a** and **1b** and involving exclusive attack of $\text{Ag}(\text{I})$ at the C-O-C fragment are excluded. (a) A common intermediate: the intermediates **I** are not observed in the NMR

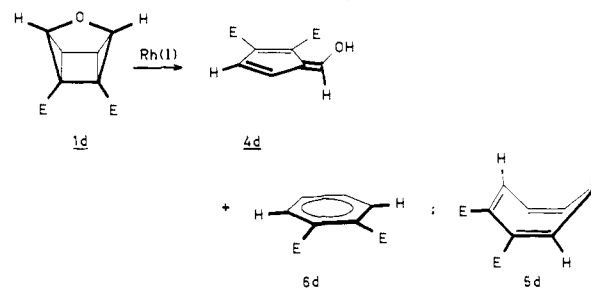


spectra during the kinetic runs, this would imply that the formation of **I** is rate determining. This seems unlikely because, if **1c** is used as starting material, one would expect an intermediate and products in which the methyl substituent is attached to the five-membered ring;⁴⁸ however these products are not formed (see text). (b) Occurrence of two parallel reactions, proceeding at the C-O-C fragment: this scheme is consistent with the



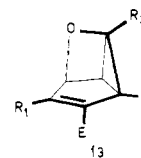
products formed in the reaction of **1c**. However, it does not explain why only **10b**-Ag should occur and not **11b**-Ag, which even might be more favorable.

- (48) Compare the relative rates of solvolysis of 1-bromocyclopropane and of 1-bromo-1-methylcyclopropane, being **1** and **40**, respectively: E. F. Cox, M. C. Caserio, M. S. Silver, and J. D. Roberts, *J. Am. Chem. Soc.*, **83**, 2719 (1961).
- (49) One may wonder why reaction of **1a** with AgClO_4 in benzene should proceed via attack at the ether oxygen atom, whereas reaction of **1a** with CCl_3COOH does not proceed in that way, although the proton is a harder Lewis acid than the silver ion and oxygen is a hard Lewis base: see R. G. Pearson, *J. Chem. Educ.*, **45**, 581, 643 (1968). However, one should bear in mind that in benzene solution one is actually not dealing with protons, but rather with dimers of trichloroacetic acid; compare ref 39.
- (50) Inductive effects play a dominant role in complexation of silver to olefins: T. Fueno, O. Kayimoto, T. Okuyama, and J. Furukawa, *Bull. Chem. Soc. Jpn.*, **41**, 782, 785 (1968). See also G. F. Koser, *Chem. Commun.* 338 (1971), for a linear free-energy correlation of the silver catalyzed reactions of substituted cubanes.
- (51) Attack of $\text{Ag}(\text{I})$ on the cyclopropyl bond bearing the ester substituent would have led to the isomeric reaction product **4** ($\text{R}_1 = \text{H}$; $\text{R}_2 = \text{CH}_3$).
- (52) A steric effect of the methyl substituent cannot be invoked as an explanation for the lack of cleavage of the $\text{O}-\text{C}(\text{CH}_3)$ bond because of the observation that **11a** and **11c** are formed at about the same rate.
- (53) The mechanism for the direct formation of **11** from **1** via an attack of silver on a lone pair of the oxygen atom is consistent with the observation that **11b** is not directly formed from **1b**: Dreiding models show that the formation of **11b**-Ag is unfavorable, because of strain due to the octamethylene chain; moreover, shielding of the oxygen atom by the octamethylene chain may also contribute to the lack of direct formation of **11b** from **1b**.
- (54) Such an idea might be derived from the fact that oxepines are in equilibrium with the benzene oxide valence isomers (the position of the equilibrium is known to depend upon the substituents;⁵⁵ it would be shifted—owing to strain—more to the side of the benzene oxide isomer if the methyl groups in **5a** are replaced by an octamethylene chain as shown by molecular models) and that $\text{Rh}(\text{I})$ complexes are capable of extruding an oxygen atom from certain benzene oxide-oxepine mixtures most probably via the benzene oxide isomer.^{56,57}
- (55) E. Vogel and H. Günther, *Angew. Chem.*, **79**, 429 (1967).
- (56) H. C. Volger, H. Hogeveen, and C. F. Roobeek, *Recl. Trav. Chim. Pays-Bas*, **92**, 1223 (1973).
- (57) Compound **5a** deoxygenates only slowly at 40–60 °C in the presence of the $\text{Rh}(\text{I})$ complex; see ref 21.
- (58) The reaction products **4d** and **5d** were characterized by comparison with ^1H NMR spectral data of authentic material; see ref 12 and P. H. Grant, R. C. Hirst, and H. S. Gutowsky, *J. Chem. Phys.*, **38**, 470 (1963), respectively. It is assumed that the formation of compounds **6d** and **5d** occurs via a



common intermediate (see text; Scheme XVI). Actually compound **5d** is not observed which means that the rate of formation of **5d** is slower than that of **6d**. The factor of 15 is the difference between the rates of formation of compounds **5a** and **6d**.

- (59) It is of interest to note that the ratio of products **5**:**4** depends on the temperature; for instance in the reaction of **1a** in benzene this ratio is ~2 (20 °C); ~4 (40 °C) and ~10 (65 °C).
- (60) It may be worthwhile to mention that, consistent with this conclusion, R_1 and R_2 do not possess analogous positions in compounds **4c** and **5c** (Scheme XV); preliminary results.
- (61) In the presence of methanol in the reaction mixture no oxepines **5** are formed (see ref 21); this may possibly be due to a coordination of methanol to rhodium, resulting in a species which no longer acts as a Lewis acid, or to the oxoquadricyclane molecule being solvated at the C-O-C fragment by methanol.
- (62) This process may be purely thermal; compare the thermal opening of the 1,5 bond in pentamethylbicyclo[3.1.0]hexenyl cation, which occurs readily at -35 °C: R. F. Childs, M. Sakai, B. D. Parrington, and S. Winstein, *J. Am. Chem. Soc.*, **96**, 6403 (1974).
- (63) We cannot exclude the possibility that the bicyclo[3.1.0]hexenyl cation loses $\text{Rh}(\text{I})$ yielding compound **13**—structure **13a** ($\text{R}_1 = \text{R}_2 = \text{CH}_3$) has been proposed previously by Vogel et al.²¹—which would be converted to **5** via the benzene oxide isomer, in a catalyzed process. However this possibility seems less likely to us because of the amount of strain energy that is necessary for the formation of **13**.



- (64) A similar effect of the octamethylene chain caused the lack of direct formation of **11b** from **1b** in the AgClO_4 catalyzed process; compare ref 53.
- (65) A close similarity is assumed with the proposed mechanisms for the $\text{Ni}(0)$ catalyzed cycloaddition of electron-deficient olefins to quadricyclane and the $\text{Ni}(0)$ catalyzed valence isomerization of quadricyclane into norbornadiene: R. Noyori, I. Umeda, H. Kawachi, and H. Takaya, *J. Am. Chem. Soc.*, **97**, 812 (1975).
- (66) Preliminary results from the reaction of [8](2,4)-3-oxaquadricyclane (structure ii in ref 38) with $\text{Rh}_2(\text{CO})_4\text{Cl}_2$ confirm the proposed mechanism; a very fast reaction occurs in which CO evolution is observed. The fast reaction of ii compared with that of **1b** is in agreement with the rhodium-catalyzed valence isomerization of quadricyclanes: H. Hogeveen and B. J. Nusse, *Tetrahedron Lett.*, 3667 (1973).
- (67) For a review of the subject of oxidative addition, see J. Halpern, *Acc. Chem. Res.*, **3**, 386 (1970).
- (68) The observation of about equal rates for the formation of **4a** and **4d** by the oxidative addition process may be compared with the rates of the $\text{Rh}_2(\text{norbornadiene})_2\text{Cl}_2$ catalyzed reactions of homocubane and 4-methylhomocubane (the rates differ by a factor of 2.5); see ref 16b.
- (69) The results from the catalyzed reactions of 2,3-dicarbomethoxy-1,4-dimethyl-7-oxanorbornadiene (NOR^*) (this is the precursor of **1a**, obtained by Drs. A. Bruggink and T. B. Middelkoop in this laboratory) allow the conclusion that most probably the 7-oxanorbornadienes are not involved in the catalyzed reactions of the 3-oxaquadricyclanes. It has been found that reaction of NOR^* with CF_3COOH leads to the formation of **7a**, whereas **1a** is converted into **3a** by CCl_3COOH or into **4a** by H_2SO_4 ; NOR^* does not react with CuCl , whereas under the same conditions **1a** is converted smoothly into **4a**; reaction of NOR^* with $\text{Pd}(\text{C}_6\text{H}_5\text{CN})_2\text{Cl}_2$ does not lead to **4a**, whereas the latter compound is formed from **1a** under the same conditions; finally, NOR^* is converted into **4a** on treatment with $\text{Rh}_2(\text{CO})_4\text{Cl}_2$, whereas under the same conditions **1a** is mainly converted into **5a**. The minor product **4a** in the latter case may formally be formed via NOR^* ; however, we have no indications for this and, in view of the above-mentioned results it seems unlikely.
- (70) A. I. Vogel, "A Textbook of Practical Organic Chemistry", 3rd ed, Longmans, London, 1956, p 163.
- (71) (a) H. Nozaki, T. Koyoma, and T. Mori, *Tetrahedron*, **25**, 5357 (1969); (b) K. Matsui, T. Mori, and H. Nozaki, *Bull. Chem. Soc. Jpn.*, **44**, 3440 (1971); (c) R. Helder, Ph.D. Thesis, University of Groningen, 1974, has described an improved synthesis of [8](2,5)furanophane.
- (72) (a) The methylene carbon atoms were observed in the region of δ 28.69–22.13. No coupling constants could be obtained because of the complexity and number of signals. (b) One of the quaternary sp^2 carbon atoms could not be determined with certainty. (c) The chemical shifts of the octamethylene chain hydrogens could not be determined because of the low concentration of **10b** in the reaction mixture. (d) Not all the quaternary carbon atoms could be determined because of the low concentration of **10b** in the reaction mixture. (e) The exact chemical shifts of the octamethylene chain carbon atoms could not be determined because of the complexity of the signals in the area of δ 36.68–22.84; neither of the coupling constants have been estimated. (f) The chemical shifts of the octamethylene chain hydrogens have not been determined. (g) Analogous to **10b** the chemical shifts of the octamethylene chain carbon atoms could not be determined (compare 72e).
- (73) H. Hogeveen and T. B. Middelkoop, *Tetrahedron Lett.*, 4325 (1973).

A Nuclear Magnetic Resonance Kinetic Study of the Acid-Catalyzed Epoxide Ring Opening of Tetramethylethylene Oxide¹

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Abstract: The kinetics of the hydrolytic ring opening of tetramethylethylene oxide (TMEO, **1**) to form pinacol (**2**) in aqueous buffers have been investigated by nuclear magnetic resonance spectroscopy using a repetitive timed integration technique. The pseudo-first-order rate plots showed excellent linearity, >87%, and yielded observed rate coefficients which were dissected into the three components, k_0 , $k_{\text{H}_3\text{O}^+}$, and k_{HA} . The velocity term, $k_{\text{HA}}[\text{HA}][\text{1}]$, arising from catalysis by molecular formic acid, leads concurrently to the formation of two products, **2** and pinacol monoformate. The overall velocity expression for the hydrolysis of **1** then is velocity = $\{k_0 + k_{\text{H}_3\text{O}^+}[\text{H}_3\text{O}^+] + k_{\text{HA}}[\text{HA}][\text{1}]\}$. Kinetic and solvent deuterium isotope effects were examined using standard procedures and were found to be $k_{\text{H}_3\text{O}^+}/k_{\text{D}_3\text{O}^+} = 0.35$, $k_{\text{HA}}/k_{\text{DA}} = 1.6$, and $k_{\text{H}_2\text{O}}/k_{\text{D}_2\text{O}} = 1.8$. The magnitude of these isotope effects, coupled with activation parameters, product analyses under strict kinetic control, nucleophilic catalysis by a buffer component, and general acid catalysis by HA, supports the conclusion that there is participation by a nucleophile (H_2O or A^-) in the various transition states associated with the ring-opening process. Pinacol is produced via k_0 , $k_{\text{H}_3\text{O}^+}$, and the component of general acid catalysis in the k_{HA} term. Pinacol monoformate is produced via the component of nucleophilic catalysis in the k_{HA} term. Mechanisms which accommodate these data and also account for the strong orientational preference in the ring-opening process of unsymmetrical epoxides are proposed.

Introduction

In a now classic kinetic investigation, Brønsted, Kilpatrick, and Kilpatrick⁴ demonstrated that the heterolytic ring fission of simple epoxides in aqueous media was a reaction characterized by several kinetically distinguishable components. These were identified as arising from the catalytic action of hydronium ion, hydroxide ion, and the solvent. Using various buffer solutions, an attempt was made to observe general catalysis, but this discovery proved elusive.

Twenty-six years later, Long and Pritchard⁵ re-examined the kinetics of epoxide hydrolysis using techniques and substrates identical with those used by Brønsted et al., but refined by ¹⁸O tracer mass spectrometry and by the study of solvent deuterium isotope effects. The latter techniques allowed Long and Pritchard to elegantly correlate each of the kinetically distinguishable catalytic components, with a characteristic reaction mechanism. In this study also the discovery of general

acid catalysis proved elusive. Since Long's original papers, several authors^{6–8} have investigated certain facets of the epoxide ring-opening problem. Though this new data was not conclusive enough to provide a definitive analysis, it has made it obvious that for epoxide hydration the previously postulated A-1 mechanism exhibits a number of characteristics associated with an A-2 process.

In this paper we describe a kinetic study of the epoxide ring opening of tetramethylethylene oxide (TMEO) by nuclear magnetic resonance spectroscopy and report that this simple saturated epoxide exhibits general acid catalysis in addition to the other traditional forms of catalysis. Because of the special nature of TMEO, certain unique mechanistic problems were encountered in attempting to rationalize our experimental findings with those of other workers. These problems were resolved with the aid of recent developments in MO theory⁹ allowing us to formulate a satisfactory description of the ring-opening process which is described herein.