Stereospecific Generation of 2-Oxyallylic Cations from Two New Sources. Steric Course of Cycloaddition to Conjugated Dienes[1a]

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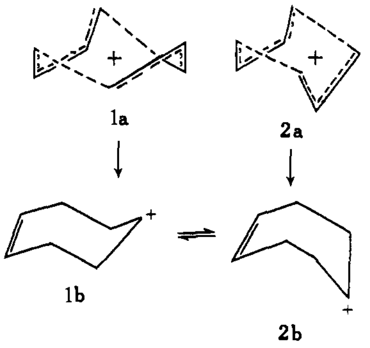
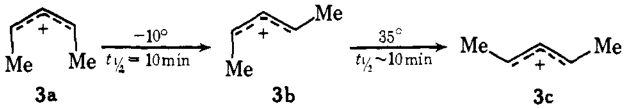
Contribution from William Ramsay and Ralph Forster Laboratories, University College, London, WC1H OAJ, England. *Received June 9, 1971*

Abstract: 2-Oxyallylic cations have been generated by two new routes: (1) a heterocyclic one starting with the highly reactive 2-dimethylamino-4-methylene-1,3-dioxolanes **4a**, **4b**, and **5**, and (2) an organometallic route using the α,α'-dibromo ketones **6a**–**d** and a zinc–copper couple in glyme. The allyl cations so produced combine with furan and cyclopentadiene to afford a comprehensive series of 8-oxabicyclo[3.2.1]oct-6-en-3-ones, *i.e.*, **7**, **8a**, **9**, **10a**, **10b**, and **10c**, and the bicyclo[3.2.1]oct-6-en-3-ones **11**, **12a**, **12b**, **13**, **14a**, and **14b**. The configuration of the epimeric methyl groups in the cycloadducts has been determined, axial methyl protons resonating in the region τ 8.70–8.85 and equatorial ones at τ 9.00–9.15. Similarly, axial protons α to the carbonyl λ are shown to resonate at lower field (τ 7.2–7.3) than equatorial ones (τ 7.8–7.9). It is shown that the six-membered ring of the bicyclo[3.2.1]oct-6-en-3-ones has a greater tendency toward flattening to a half-chair than that of the 8-oxabicyclo[3.2.1]oct-6-en-3-ones. From the configuration of the cycloadducts formed and stereochemical information built into the heterocyclic precursors **4a** + **4b**, it has been established that the 1,3-dimethyl-2-formoxyallyl cation is formed stereospecifically in the W configuration **16a**. Similarly, on debromination of 2,4-dibromo-3-pentanone (**6d**) in glyme the W cation is formed at least preferentially. Heterocycle **5** gives rise to the 1,1,3-trimethylallyl cation of configuration **17**. In all the cycloadditions studied the boat-like transition state **2a** is favored over the chair alternative **1a**, and for furan more so than for cyclopentadiene.

We have established previously that the simple 2-methylallyl cation cycloadds to cyclopentadiene at least preferentially *via* the chair-like transition state **1a** rather than the boat alternative **2a**.[1b] The distinction of **1a** and **2a** was achieved by stereospecific trapping of a **1b** derivative from the endo face before any conformational flipping into **2b** could occur. Apart from this work no more information has come forward on the question of chair *vs.* boat transition states in $4 + 3 \rightarrow 7$ cycloadditions.[2]



If one were to succeed in generating a terminally substituted allyl cation stereospecifically and then cycloadd it to a conjugated diene, the steric course of the ring formation could be deduced from the ratio of stereoisomeric adducts that arise. Of course, long-lived allyl cations of known configuration have been described previously. For instance, Deno has identified a variety of cyclic allylic species, especially cyclopentenyl and cyclohexenyl cations.[3] More recently the cis,cis- or U-shaped 1,3-dimethylallyl cation **3a** has been observed in SbF_5–SO_2ClF, and it has been shown that it rearranges into the cis,trans species **3b** which finally forms **3c**; the trans,trans form has been estimated to be more stable than cis,cis by 6.4 kcal/mol.[4a] However, it is interesting that considerable efforts to trap these cations by conjugated dienes have been unsuccessful;[4b] presumably the super acid present tends to destroy the conjugated diene before it can react with the allyl cation.[1c]



3a **3b** **3c**

We now wish to record two new and simple routes toward stabilized allyl cations which can also combine with conjugated dienes to afford a comprehensive series of bridged cyclohept-4-enones. Besides having synthetic interest the reactions to be described yield insight into the stereochemistry and mechanism of formation of 2-oxyallylic cations, the nature of the transition state in the ensuing cycloaddition, and the conformation of bicyclo[3.2.1]oct-6-en-3-ones and 8-oxabicyclo[3.2.1]oct-6-en-3-ones.

Results

In the present study allyl cations were generated from two precursors: (1) the 2-dimethylamino-4-methylene-1,3-dioxolanes **4a** + **4b** as well as **5**,[5] which were

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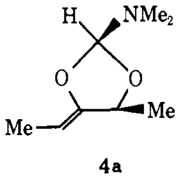
(1) (a) Work reported in part at the International Symposium on the Chemistry of Small Ring Compounds and Activated Multiple Bonds, Louvain, Belgium, Sept 1971; (b) H. M. R. Hoffmann and D. R. Joy, *J. Chem. Soc. B*, 1182 (1968); (c) H. M. R. Hoffmann, D. R. Joy, and A. K. Suter, *ibid.*, 57 (1968); *cf.* also H. M. R. Hoffmann, G. F. P. Kernaghan, and G. Greenwood, *ibid.*, 2257 (1971).

(2) (a) For the ring size criterion of cycloadditions see R. Huisgen, *Angew. Chem., Int. Ed. Engl.*, 7, 321 (1968); (b) for a mechanistic classification see R. B. Woodward and R. Hoffmann, *ibid.*, 8, 781 (1969).

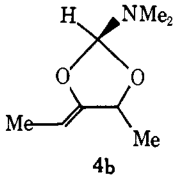
(3) N. C. Deno, *Progr. Phys. Org. Chem.*, 2, 129 (1964).

(4) (a) P. v. R. Schleyer, T. M. Su, M. Saunders, and J. C. Rosenfeld, *J. Amer. Chem. Soc.*, 91, 5174 (1969); (b) P. v. R. Schleyer, personal communication, Sept 1970.

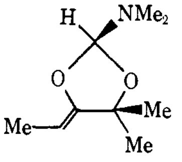
(5) H. M. R. Hoffmann, K. E. Clemens, E. A. Schmidt, and R. H. Smithers, *J. Amer. Chem. Soc.*, 94, 3201 (1972).



4a

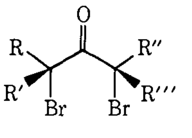


4b



5

allowed to react with furan at room temperature, and (2) the α,α-dibromo ketones **6a–d**, which were debrominated with a zinc–copper couple *in situ*. In this cycloaddition acetone was used initially for the reactions with furan, but it was found later that glyme was far more effective as a solvent. In acetone solvent the majority of product was found to be diacetone alcohol, parent ketone, an unknown compound, as well as the cycloadduct. In striking contrast when glyme was used the cycloaddition was very clean, the desired cycloadduct and unreacted dibromo ketone generally forming a high percentage of the recovered solution. By adding the zinc–copper couple in portions, the per cent yield could be increased further owing to a higher conversion of the dibromo ketone. The cycloadducts formed were isolated by preparative glc (20 ft Carbowax 20M, 120°) as colorless, pleasant smelling solids which melted around room temperature or below. Generally, the cyclopentadiene adducts had a shorter retention time than the presumably more polar and higher melting furan adducts. Considerable difficulties were encountered in separating some of the epimeric adducts formed. For example, attempts to resolve **10a**, **10b**, and **10c** on Carbowax 20M and on ordinary silicone oil columns were not successful. However, the epimers could finally be separated on a dinitrophenyl naphthyl ether column and on a silicone oil capillary column which was connected to a mass spectrometer. As the various epimers left the glc column, the homogeneity of each peak was further established by repeated rapid scanning of the mass spectrum. Significantly, the first most volatile epimer was in each instance the cis diaxial epimer. Thus, **10b** came off the column faster than **10a**, **14b** faster than **14a**, and **12b** faster than **12a**.[6] Table I gives a selection of cycloadducts which we have obtained so far. Turro and his coworkers deserve credit for having previously prepared four of these cycloadducts,[7] *i.e.*, **7**, **8a**, **9**, and **13**. The nmr signals of all epimeric methyl groups can now be assigned; *e.g.*, the 2,2,4-trimethyl-8-oxabicyclo[3.2.1]oct-6-en-3-one reported[7b] is in fact epimer **8a** (*cf.* below).



6a, $R = R' = R'' = R''' = Me$
b, $R = R' = R'' = Me;\ R''' = H$
c, $R = R' = Me;\ R'' = R''' = H$
d, $R = R'' = Me;\ R' = R''' = H$

Configurational Assignments from Nmr and Ir Spectra

A priori, the six-membered ring of a bicyclo[3.2.1]oct-6-en-3-one could be present in a chair, flattened chair, or boat conformation; furthermore, the methyl groups can occupy the exo or endo configuration. A secure assignment can be made on the basis of the combined nmr and ir data. In the furan adducts **8a**, **9**, **10a**, **10b**, and **10c**, the nmr signals of the protons α to the carbonyl group fall into the range (i) τ 7.2–7.3 and (ii) τ 7.8–7.9. Further, the downfield signals show splitting due to coupling to the vicinal bridgehead proton, $J_{vic} = 4\text{–}5$ Hz, while the upfield signals show $J_{vic} \sim 0$ Hz.

Generally, axial protons in cyclohexanes resonate at higher field than equatorial ones.[8] However, in the case of α-halocyclohexanones axial protons have been observed to be deshielded with respect to the equatorial protons,[9] an effect which we now find also for the chemical shift of the *halogen-free* cyclohexanones. A coupling constant of $J_{vic} = 5$ Hz suggests a torsional angle of *ca.* 50° for the axial proton with the bridgehead proton, *i.e.*, a chair or flattened chair, but not a boat form where the torsional angle would be either *ca.* 100 or 20° and J_{vic} as calculated from the Karplus equation would have to be correspondingly smaller (J = 0–1 Hz) or larger (J = 6–8 Hz).

Equatorial–equatorial coupling amounts to $J_{vic} \sim 0$ Hz; *i.e.*, the torsional angle is unfavorable for coupling which could be reduced further owing to the presence of the nearly antiperiplanar electronegative bridge oxygen.[8a] Decoupling experiments suggest that any further fine structure of the equatorial signals is due to W coupling of the cis diequatorial protons.

Interestingly, the methyl proton resonances of our adducts fall again into two sharply demarcated regions: (i) τ 8.70–8.85 and (ii) τ 9.00–9.15. Clearly, the downfield region τ 8.70–8.85 can be assigned to axial and the region τ 9.00–9.15 to equatorial protons in a self-consistent pattern.[10] We suggest that the downfield shift of the axial methyl protons is caused by a simple stereoelectronic effect in that the π system of the carbonyl group interacts preferentially with the axial $C\text{–}CH_3$ σ bond.

The nmr spectra of the cyclopentadiene adducts are more complicated owing to the methylene bridge ($Z = CH_2$), but further conformational insight can be gained from the ir spectra. The carbonyl stretching frequencies of these adducts (Table II) fall into the region observed for other cyclohexanones (1709–1714 cm^{-1}) with the notable exception of the tetramethylcyclohexanone derivative **11** (1695 cm^{-1}) where steric congestion of the carbonyl is expected to lead to an expansion of the C–CO–C bond angle, *i.e.*, a flattening of the cyclohexanone chair, and a concomitant depression

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[6] *Cf.* E. L. Eliel, N. A. Allinger, S. J. Angyal, and G. A. Morrison, "Conformational Analysis," Interscience, New York, N. Y., 1965, pp 177–178.

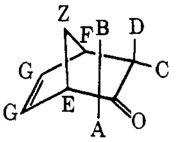
[7] (a) N. J. Turro, S. S. Edelson, J. R. Williams, T. R. Darling, and W. B. Hammond, *J. Amer. Chem. Soc.*, **91**, 2283 (1969); (b) N. J. Turro, S. S. Edelson, and R. B. Gagosian, *J. Org. Chem.*, **35**, 2058 (1970).

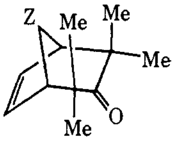
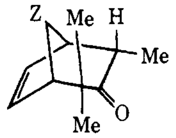
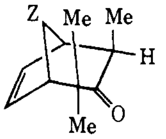
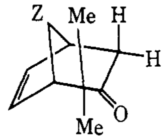
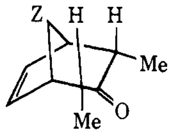
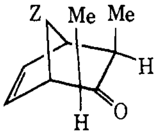
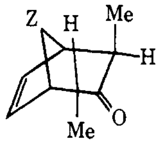
[8] (a) *Cf.* L. M. Jackman and S. Sternhell, "Applications of Nuclear Magnetic Resonance Spectroscopy in Organic Chemistry," 2nd ed, Pergamon Press, Oxford, 1969; (b) R. U. Lemieux, R. K. Kullnig, H. J. Bernstein, and W. G. Schneider, *J. Amer. Chem. Soc.*, **80**, 6098 (1958).

[9] A. Baretta, J. P. Zahra, B. Waegell, and C. W. Jefford, *Tetrahedron*, **26**, 15 (1970); E. W. Garbisch, *J. Amer. Chem. Soc.*, **86**, 1780 (1964); *J. Org. Chem.*, **30**, 2109 (1965); K. M. Wellman and F. G. Bordwell, *Tetrahedron Lett.*, 1703 (1963); A. Nickon, M. A. Castle, R. Harada, C. E. Berkoff, and R. O. Williams, *J. Amer. Chem. Soc.*, **85**, 2185 (1963); *cf.* also ref 8a.

[10] The shorter glc retention time of **10b** (**12b**, **14b**) *vs.* **10a** (**12a**, **14a**) and a study on conformationally anchored α-methylcyclohexanones (*cf.* M. Fétizon, J. Gore, P. Laszlo, and B. Waegell, *J. Org. Chem.*, **31**, 4047 (1966); H. O. House, B. A. Tefertiller, and H. D. Olmstead, *ibid.*, **33**, 935 (1968)) concur with our assignments.

Table I. Nmr Spectra ($\tau_{\text{TMS}}^{\text{CCl}_4}$) of 8-Oxabicyclo[3.2.1]oct-6-en-3-ones (Z = O) (**7**, **8a**, **9**, **10a**, **10b**, **10c**) and Bicyclo[3.2.1]oct-6-en-3-ones (Z = CH_2) (**11**, **12a**, **12b**, **13**, **14a**, **14b**)



	 Z = O **7** Z = CH_2 **11** A	 **8a** **12a** B	 **8b** **12b** C	 **9** **13** D	 **10a** **14a** E	 **10b** **14b** F	 **10c** **14c** G
7[a]	9.15 s (6 H)	8.73 s (6 H)			5.76 s (2 H)		3.78 s (2 H)
8a[b]	9.13 s (3 H)	8.75 s (3 H)	9.11 d, J = 7 Hz (3 H)	7.19 d (J = 5 Hz) of q (J = 7 Hz) (1 H)	5.66 d, $J \sim 1$ Hz (1 H)	5.34 d (J = 5 Hz) of d ($J \sim 1$ Hz) (1 H)	3.65–3.81 m (2 H)
9[a]	9.09 s (3 H)	8.75 s (3 H)	7.91 C of CD quartet ($J_{C,D}$ = 16 Hz) (1 H)	7.25 D of CD quartet ($J_{C,D}$ = 16 Hz, $J_{D,F}$ = 5 Hz) (1 H)	5.63 s (1 H)	5.11 br d, J = 5 Hz (1 H)	3.56–3.82 m (2 H)
10a	9.10 d, J = 7 Hz (6 H)			7.33 d (J = 5 Hz) of q (J = 7 Hz) (2 H)	5.28 d, J = 5 Hz (2 H)		3.72 br s (2 H)
10b		8.73 d, J = 7 Hz (6 H)	7.87 q, J = 7 Hz (2 H)		5.48 br s (2 H)		3.78 br s (2 H)
10c[c]	9.11 d, J = 7 Hz (3 H)	7.33 d (J = 5 Hz) of q (J = 7 Hz) (1 H)	7.83 q (1 H)	8.73 d, J = 7 Hz (3 H)	5.35 d, J = 5 Hz (1 H)	5.46 br s (1 H)	3.75 m (2 H)
11	9.05 s (6 H)	8.84 s (6 H)			7.64–8.30 m (4 H)[d]		3.89 br s (2 H)
12a	9.04 s (3 H)	8.86 s (3 H)	9.05 d, J = 6.5 Hz (3 H)	7.36–8.18 m (5 H)[d]			3.83–4.04 m (2 H)
12b	Obscured	8.88 s			Obscured		
13[a]	9.00 s (3 H)	8.83 s (3 H)		7.20–8.25 m (6 H)[d]			3.75–4.05 m (2 H)
14a	9.05 d, J = 7 Hz (6 H)			7.25–8.13 m (6 H)[d]			3.96 br s (2 H)
14b		8.84 d, J = 7 Hz (6 H)			Obscured		
14c[e]	9.06 d, J = 7 Hz	8.85 d, J = 7 Hz			Obscured		

[a] Spectrum given in ref 7a confirmed. [b] Spectrum given in ref 7b resolved further. [c] The signals of **10c** are discernible after adding nmr shift reagent. [d] Protons of bridging methylene (Z = CH_2) included. [e] Tentative identification only; see Experimental Section.

Table II. Ir Carbonyl Stretching Frequencies (cm^{-1}) of Cycloadducts[a]

7 (1710)	**8a** (1715)	**9**[b] (1720)	**10a** + **10b** + **10c** (1715)[c]
11 (1695)	**12a** + **12b** (1707[c])	**13**[b] (1714)	**14a** + **14b** (1710)[c]

[a] Measured on neat compounds. [b] See ref 7a. [c] This band is not sufficiently resolved to allow individual assignments.

of the carbonyl absorption.[11] Interestingly, the cyclopentadiene adducts show a consistently lower carbonyl stretching frequency than the corresponding furan adducts and it seems clear that the former adducts have a greater propensity toward flattening of the chair than the furan adducts. Obviously, an approach toward a half-chair of the cyclohexanone type will also make a distinction of axial and equatorial methyl groups more tenuous, and it is interesting that the chemical shift difference between epimeric methyl groups is consistently less for the bicyclo[3.2.1]oct-6-en-3-ones than for the 8-oxa analogs (*cf.* Table I). A simple and in our opinion convincing rationale for these conformational differences is provided by the inverse reflex effect[12] (Figure 1). On introduction of an unsaturated bracket into the 1,5-diaxial positions of a cyclohexanone chair, the 2,4-diaxial substituents are pried apart and thec hair

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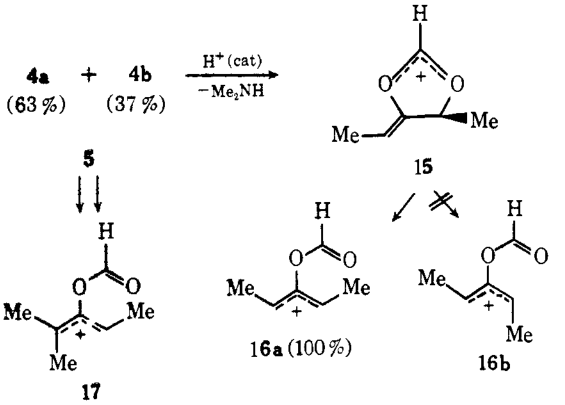
(11) J. O. Halford, *J. Chem. Phys.*, **24**, 830 (1956); *cf.* also ref 6, p 197; and C. J. W. Brooks, G. Eglinton, and L. Hanaimeh, *Spectrochim. Acta*, **22**, 131, 161 (1966).

(12) B. Waegell and G. Ourisson, *Bull. Soc. Chim. Fr.*, 495, 496, 503 (1963); B. Waegell and C. W. Jefford, *ibid.*, 844 (1964); C. W. Jefford, A. Baretta, J. Fournier, and B. Waegell, *Helv. Chim. Acta*, **53**, 1180 (1970); *cf.* also C. W. Jefford and U. Burger, *Chimia*, **24**, 385 (1970), and references cited therein.

flattens (A → B). Now, since the methylene bridge is longer than the oxygen bridge (the C–C and C–O bond distances are *ca.* 1.54 and 1.43 Å, respectively), flattening to a half-chair is expected to be more severe for the bicyclo[3.2.1]oct-6-en-3-ones than for the 8-oxa analogs.

The mass spectra of the bicyclics show an intense peak due to the loss of the ketene and ketene plus hydrogen moieties. Further, in those adducts like the trimethylated and geminal dimethylated species where a choice of alkylated ketene is possible, the more intense peak corresponds to the loss of the more alkylated ketene. Interestingly, the selectivity toward loss of more alkylated ketene is more marked for the oxygen-bridged than for the corresponding methylene-bridged ketones.

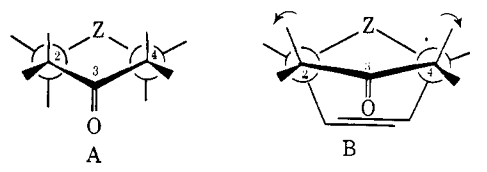
Stereochemistry and Mechanism. Of the cycloadditions studied, the most informative mechanistically are those starting with the heterocyclic precursors **4a** + **4b** and **5**. These reactions can be monitored conveniently by the liberation of gaseous dimethylamine and they can be suppressed by adding an anhydrous base such as 2,6-lutidine. Clearly, loss of dimethylamine is catalyzed by traces of weak acid, supplied, *e.g.*, by traces of an enol or adventitious moisture, and the obvious rational intermediate formed from **4a** + **4b** is the dioxolenium ion **15**. Now just as its precursors, **15** is racemic and could open *a priori* to the 1,3-dimethyl-2-formoxyallyl cation of either W configuration **16a** or sickle geometry **16b**. However, since the methyl groups in the derived cycloadduct **10a** are cis to each other, it may be concluded that the W-shaped allylic cation **16a** is formed to the exclusion of the sickle form **16b**; *i.e.*, opening of **15** to **16a** is 100% stereospecific. Similarly, the cationic intermediate arising from heterocycle **5** can only be the W-shaped species **17**, since the single methyl group is locked from the very beginning in the configuration cis to the vicinal formoxy grouping.



Given the configuration of allyl cation intermediates and cycloadducts, the steric course of the cycloadditions follows from the ratio of stereoisomeric cis adducts as shown in Scheme I, equatorial methyls indicating a boat-like and axial methyls a chair-like transition state.

While the nature of the intermediates of the debromination of α,α′-dibromo ketones may seem less certain, it is a minimum prerequisite that an allylic cation be formed again by way of an SN1 reaction and that it be sufficiently long lived to combine with a conjugated diene. A plausible intermediate is the zinc enolate **18**, which is reminiscent of the Reformatsky reagent[13] and in which zinc is expected to be four-coordinate thus attaining the electron configuration of krypton. In the next stage rotation about the C–O bond could lead to internal complexation of the second bromine with formation of **19**. SN1 heterolysis of **19** or a related 2-oxyallylic species can then generate the allylic cation required for the cycloaddition. Whatever the detailed mechanism there is little reason to presume that the steric course of debromination in acetone and glyme is basically different from that in dimethylformamide.[3] Specifically, it seems likely that the single methyl group attached to the olefinic terminus in **18** is cis to the vicinal oxygen in analogy to the formation of only those 4-ethylidene-1,3-dioxolanes in which the methyl group of the ethylidene grouping is cis to the vicinal oxygen (*cf.* **4a** + **4b** and **5**).[3]

Now, since the trimethylated α,α′-dibromo ketone **6b** yields furan adduct **8a** in at least 98% epimeric purity and since **8a** is formed independently from furan and heterocycle **5**, a W-shaped 1,1,3-trimethyl-2-oxyallyl cation similar to **17** is implicated as the reactive species

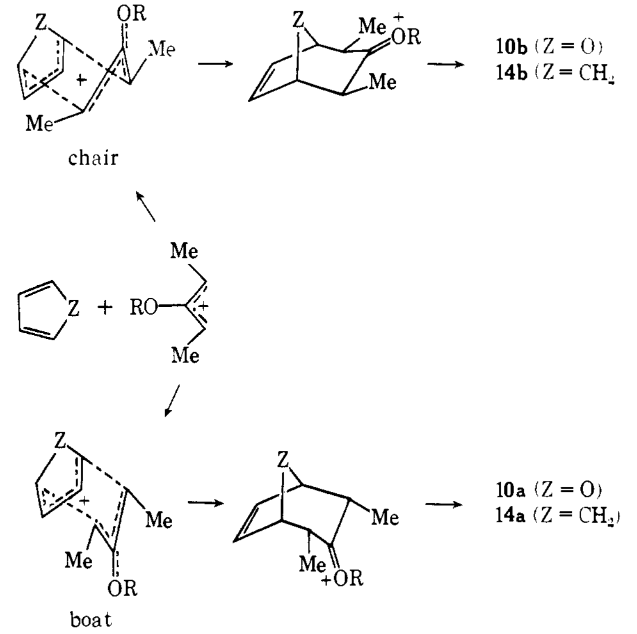


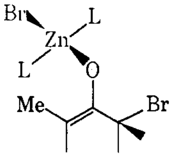
A normal chair conformation of cyclohexanone

B inverse reflex effect

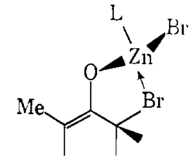
Figure 1. Flattening of a six-membered ring toward a half-chair by the inverse reflex effect.

Scheme I





18, L = solvent



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(13) *Cf.* W. R. Vaughn and H. P. Knoess, *J. Org. Chem.*, **35**, 2394 1970).

Table III. Boat *vs.* Chair Transition States in Cycloadditions of 2-Oxyallyl Cations to Conjugated Dienes

No.	Diene	Allyl cation	Source[a]	Isomers formed	Boat *vs.* chair transition state[b]
1	Furan	1,3-Dimethyl-2-oxy	H	**10a**[c]	boat
2	Furan	1,3-Dimethyl-2-oxy	O	**10a**:**10b**:**10c** = (81:10:9)[d]	8.1:1
3	Cyclopentadiene	1,3-Dimethyl-2-oxy	O	**14a**:**14b** = 1.67:1[d]	1.67:1
4	Furan	1,1,3-Trimethyl-2-oxy	H	**8a**[c]	boat
5	Furan	1,1,3-Trimethyl-2-oxy	O	**8a**[d]	boat
6	Cyclopentadiene	1,1,3-Trimethyl-2-oxy	O	**12a**:**12b** = 3.8:1[d]	3.8:1

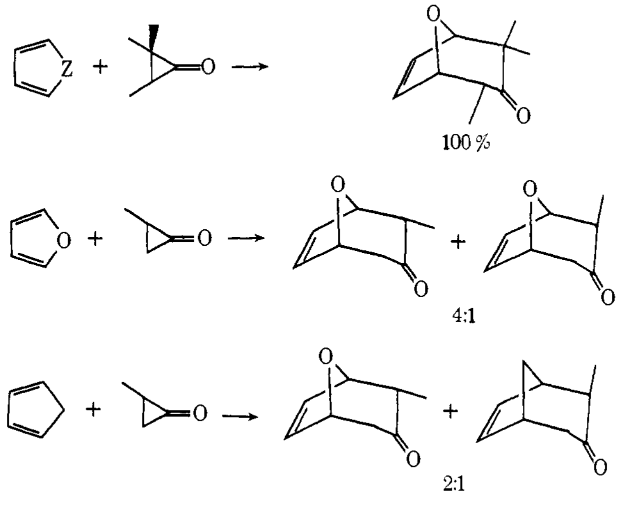
[a] H = heterocyclic precursor; O = organometallic precursor. [b] These terms refer to the conformation of the seven-membered ring. [c] Only one compound detectable by nmr; it is considered that *ca.* 5% of any isomer would have been discernible. [d] Determined by glc.

entering into the cycloadditions in solvents glyme and acetone. Likewise, a W-shaped 1,3-dimethyl-2-oxyallyl cation similar to **16a** must be involved in the formation of the cis diequatorial adducts **10a** and **14a** and must also enter into the formation of cis diaxial **10b** and **14b**, given the exclusive generation of cis zinc enolates (*cf.* **18**). The equatorial–axial adduct **10c**, which is a minor product, can be formed by several routes and its origin is being studied further.

From the ratio of isomers formed (Table III), one can see that the boat transition state is generally preferred. Within the limits of nmr detectability, the cycloadditions of the heterocyclic precursors **4a** + **4b** (no. 1) and **5** (no. 4) adhere completely to the boat geometry. However, this preference is somewhat reduced in the organometallic route (no. 2), especially so with cyclopentadiene (no. 3). Presumably, several factors including secondary orbital interactions[1b] contribute to the observed stereochemical preference and the limited results available do not yet justify a more detailed discussion. However, one should bear in mind that the general tendency toward flattening of the six-membered ring is more pronounced for Z = CH_2 than for Z = O as shown above. This factor is expected to destabilize the seven-membered boat transition state in cycloadditions involving cyclopentadiene as indeed observed.

Previously, Turro and his coworkers have added various cyclopropanones to furan and cyclopentadiene and described cycloadducts[7] the configuration of which can now be assigned as shown (Scheme II). Interestingly, trimethylcyclopropanone, like our two precursors of the 1,1,3-trimethyl-2-oxyallylic cation which has a defined geometry (*cf.* Table II, no. 4, 5), has been reported to afford one adduct,[7b] the single methyl group which must be equatorial as in **8a**. The nature of the reactive intermediate in cycloadditions of cyclopropanones to conjugated dienes has remained in the dark.[14] The results in Scheme II would match the pattern unfolded here, if an open allyl cation were formed in which any single methyl group is cis to the neighboring oxygen.

Scheme II



Finally it is worthy of note that the *in situ* debromination of α,α'-dibromo ketones in glyme with a zinc–copper couple provides a general and very simple route to seven-membered rings. For example, after their extraction with pentane from the crude reaction mixture the adducts **10a**, **10b** + **10c**, and **14a** + **14b** were almost pure judging by the nmr spectra and glc. The cycloaddition described is also applicable to open-chain dienes such as butadiene.[15]

Experimental Section

Nmr spectra were recorded on a Varian 100-MHz instrument and are listed in Table I. Ir spectra (*cf.* Table II) were taken on a Perkin-Elmer 257 grating spectrophotometer. Analytical glc was performed on a Griffin flame ionization chromatograph and preparative glc on a Hewlett-Packard 776 preparative gas chromatograph. Combined glc–mass spectral analyses were carried out by Dr. B. Willhalm (Firmenich & Cie, Geneva) using a specially designed glass capillary silicone oil column connected to a mass spectrometer.

Cycloaddition Procedure. (1). From 2-Dimethylamino-4-methylene-1,3-dioxolanes. 4-Ethylidene-5-methyl-2-dimethylamino-1,3-dioxolane (**4a** + **4b**), which was present in a 5:3 mixture, was prepared as described[5] and kept with a fivefold excess of furan for 36 hr at room temperature. After evolution of dimethylamine had stopped, the reaction solution was worked up by removing furan by rotary film evaporator leaving *endo,cis*-2,4-dimethyl-8-oxabicyclo[3.2.1]oct-6-en-3-one (**10a**) in *ca.* 90% yield. In contrast to the preparation of **10a** from α,α'-dibromo ketone **6d** and zinc–copper couple *in situ* (*cf.* below), only the cis diequatorial isomer was discernible by nmr in the present experiment.

Under the same conditions 4-ethylidene-5,5-dimethyl-2-dimethylamino-1,3-dioxolane (**5**) and furan furnished *endo*-2,2,4-trimethyl-8-oxabicyclo[3.2.1]oct-6-en-3-one (**8a**) (*ca.* 60%). The nmr spectrum of **8a**, which could be resolved further on our instrument (*cf.* Table I), was identical with that reported for 2,2,4-trimethyl-8-oxabicyclo[3.2.1]oct-6-en-3-one of unknown configuration.[7b] The cycloaddition is apparently acid catalyzed, since it could be suppressed if scrupulously dried and purified starting

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(14) S. S. Edelson and N. J. Turro, *J. Amer. Chem. Soc.*, **92**, 2770 (1970).

(15) K. E. Clemens, unpublished work; after publication of our earlier work and completion of our present studies[16] R. Noyori, S. Makino, and H. Takaya, *J. Amer. Chem. Soc.*, **93**, 1272 (1971), have also recognized the utility of α,α-dibromo ketones in cycloadditions to conjugated dienes.

(16) R. H. Smithers, Ph.D. Thesis, London, 1970; K. E. Clemens, Ph.D. Thesis, London, 1971.

materials were used. The reaction was also slowed down in the presence of 2,6-lutidine.

Various attempts to induce cycloaddition of 4-isopropylidene-5,5-dimethyl-2-dimethylamino-1,3-dioxolane[5] and furan at room temperature and at 60° were not successful. However, 4,4-dimethyl-2-dimethylamino-5-methylene-1,3-dioxolane[5] and furan on being left at room temperature showed indications from the nmr spectrum to have formed some adduct **9**.[7a]

(2). Debromination of α,α'-Dibromo Ketones with Zinc–Copper Couple *in Situ*. The α,α'-dibromo ketone (**6a–d**) (5 g) prepared as described previously[5] was dissolved in 10 ml of solvent (acetone or glyme) and stirred dropwise into a suspension of a zinc–copper couple[17] (3 molar equiv of dibromo ketone) in 25 ml of conjugated diene and solvent (50:50 v/v) under nitrogen at −5°. After complete addition the mixture was allowed to reach room temperature, and then the excess of the metal was filtered off. The excess of the diene was stripped off on a rotary film evaporator, and then solvent was removed until the solution began to turn cloudy. At this stage water (75 ml) was added and the resulting zinc hydroxide filtered off. The flask and zinc hydroxide were thoroughly washed with pentane and the washings collected in a separating funnel. The contents was shaken, the organic layer was separated, washed with water, dried ($MgCO_3$), and filtered, and pentane was stripped off. (In later preparations of the cyclopentadiene adducts **12a** + **12b** and **14a** + **14b**, the procedure was modified by using less glyme and conjugated diene; see below.)

The products were subjected to preparative glc (20 ft × $^3/_4$ in. Carbowax 20M column, 100–120°, 0.336 l./cm flow rate) whence the following cycloadducts were obtained: 2,2,4,4-tetramethyl-8-oxabicyclo[3.2.1]oct-6-en-3-one (**7**),[7a] yield *ca.* 43% from acetone solvent; *endo*-2,2,4-trimethyl-8-oxabicyclo[3.2.1]oct-6-en-3-one (**8a**),[7b] yield *ca.* 35% in acetone solvent. The compound was also prepared several times as detailed for **10a** + **10b** + **10c** below and the nmr spectrum was scanned at low sweep rates from τ 8.6 to 9.2 to search for the epimeric *exo*-2,2,4-trimethyl derivative **8b**; had it been formed, it would be present in 5% or less. The epimeric purity of the product was confirmed by high resolution glc, which would have uncovered *ca.* 1% of **8b**. 2,2-Dimethyl-8-oxabicyclo[3.2.1]oct-6-en-3-one (**9**) was identified by its nmr spectrum[7a] and its molecular ion *m/e* 152; yield *ca.* 20% from acetone solvent.

***endo,cis*-2,4-Dimethyl-8-oxabicyclo[3.2.1]oct-6-en-3-one (10a), *exo,cis*-2,4-Dimethyl-8-oxabicyclo[3.2.1]oct-6-en-3-one (10b), and *exo,endo*-2,4-Dimethyl-8-oxabicyclo[3.2.1]oct-6-en-3-one (10c).** Furan (12.5 ml) and zinc–copper couple[17] (1 g) in glyme (12.5 ml) were cooled down to −15 to −10°, and then 2,4-dibromo-3-pentanone[5] (**6d**) (5 g, redistilled) in glyme (10 ml) was stirred dropwise into the mixture at −10°. After complete addition of the dibromo ketone, the mixture was stirred for 0.5 hr at −10°, and then a second portion of zinc–copper couple (1 g) was added through a powder dropping funnel. After stirring for 0.5 hr, two further portions of zinc–copper couple (1 g each) were added at 0.5-hr intervals. The product was worked up in the usual way. On evaporation of pentane a colorless liquid remained which turned solid on standing in the refrigerator, yield *ca.* 85%. The product, which was almost pure and melted above room temperature, was subjected to preparative glc and the three isomers **10a**, **10b**, and **10c** were collected in a ratio of 9:1:1, as determined by nmr integration of the bridgehead protons after addition of the shift reagent tris(dipivalomethanato)europium(III) in $CDCl_3$. An independent, more precise determination of the product ratios by glc gave **10a** (81%), **10b** (10%), and **10c** (9%); the distinction of **10b** and **10c** here rests on the assumption that the cis diaxial epimer **10b** has the shorter retention time than **10c**. The retention time of **10a** is longest (silicone oil and dinitrophenyl naphthyl ether column).

Decoupling of the bridgehead protons confirmed coupling to the axial protons (J_{vic} = 5 Hz). *Anal.* Calcd for $C_9H_{12}O_2$: C, 71.00; H, 7.96. Found: C, 71.04; H, 8.01. The mass spectra of **10a**, **10b**, and **10c** were scanned individually, the spectrum of each compound being recorded at the beginning and end of the glc peak. There was no discernible difference in fragmentation pattern and not even in relative intensities for the three isomers.

In a separate experiment the nmr spectrum of the reaction mixture was scanned to investigate the possibility of epimerization of the products under the experimental conditions. Spectra were recorded after reaction for 0, 0.5, and 2 hr at −10° and 3 days at room temperature. While the accuracy of this method left a lot to be desired, a change in the ratio of **10a**:**10b** was not discernible.

2,2,4,4-Tetramethylbicyclo[3.2.1]oct-6-en-3-one (11) was obtained from cyclopentadiene and 2,4-dibromo-2,4-dimethyl-3-pentanone (**6a**) and zinc–copper couple[17] in glyme, yield *ca.* 65%. *Anal.* Calcd for $C_{12}H_{18}O$: C, 80.84; H, 10.18. Found: C, 80.67; H, 10.25.

***endo*-2,2,4-Trimethylbicyclo[3.2.1]oct-6-en-3-one (12a) and *exo*-2,2,4-Trimethylbicyclo[3.2.1]oct-6-en-3-one (12b).** Freshly distilled cyclopentadiene (5 g) and zinc–copper couple[17] (1 g) in glyme (5 ml) were cooled to −5 to 0° and then 2,4-dibromo-2-methyl-3-pentanone (**6b**) (5.2 g) in glyme (10 ml) was added dropwise to the stirred suspension at −5°. After complete addition three further portions of zinc–copper couple (1 g each) were added through a powder funnel, and then the product was isolated as described; yield *ca.* 60% from glyme. Glc–mass spectral analysis revealed the presence of **12a** and **12b** in a ratio of 3.8:1, the cis diaxial epimer **12b** having the shorter retention time (silicone oil column). *Anal.* Calcd for $C_{11}H_{16}O$: C, 80.42; H, 9.83. Found: C, 80.25; H, 9.89. The magnetic resonance signals of the methyl protons of the minor isomer **12b** were largely obscured by the signals from **12a** (*cf.* Table I) even at low sweep rates (250-Hz sweep width). However, a singlet at τ 8.88 (methyl group B in **12b**; *cf.* Table I) and a peak at τ 8.77 (low-field half of presumed doublet due to methyl group D) were visible; the intensity of the peak at τ 8.88 was twice that of the peak at τ 8.77. The ratio of **12a**:**12b** was determined by cutting out and weighing the expanded nmr peak at τ 8.86 and the low-field one at τ 8.77 and allowing for overlap of the upfield half of the presumed doublet with the major peak at τ 8.86; **12a**:**12b** was found to be 3.85:1, in excellent agreement with the reliable ratio obtained by glc integration. The mass spectra of **12a** and **12b** were recorded individually at the beginning as well as at the end of the glc peak. There was no discernible difference in fragmentation pattern and not even in relative intensities for the two isomers.

2,2-Dimethylbicyclo[3.2.1]oct-6-en-3-one (13)[7a] was obtained from cyclopentadiene and 1,3-dibromo-3-methyl-2-butanone (**6c**), yield *ca.* 30% (20% dibromo ketone **6c** recovered). As in the preparation of cycloadduct **9** it is advantageous to use 3-bromo-1-iodo-3-methyl-2-butanone[5] instead of **6c**.

***endo,cis*-2,4-Dimethylbicyclo[3.2.1]oct-6-en-3-one (14a) and *exo,cis*-2,4-Dimethylbicyclo[3.2.1]oct-6-en-3-one (14b).** Freshly distilled cyclopentadiene (5 g) and zinc–copper couple[17] (1 g) in glyme (5 ml) were cooled to −15 to −10°, and then 2,4-dibromo-3-pentanone (**6d**) (5 g, redistilled) in glyme (5 ml) was added dropwise to the stirred suspension below −10°. After complete addition three further portions of zinc–copper couple (1 g each) were added at 0.5-hr intervals, and then the product was isolated as described above. *Anal.* Calcd for $C_{10}H_{14}O$: C, 79.94; H, 9.40. Found: C, 79.71; H, 9.43. The product appeared as a broad peak on Carbowax. However, **14a** could be partially separated from **14b**, the first faster moving cut containing **14a**:**14b** in a ratio of 1:3 and the second cut in a ratio of 3:1. The two peaks were cleanly separated on a 20-ft dinitrophenyl naphthyl ether column (144°) and on a silicone oil capillary column. In all cases the major isomer **14a** had the longer retention time. The peak ratio **14a**:**14b** = 1.67:1, no **14c** being discernible in this experiment; it is considered that even 1% would have been detected by glc. The mass spectra of **14a** and **14b** were scanned individually as the compounds came off the silicone oil column. The fragmentation pattern and the relative intensities for **14a** were the same as those for **14b**. In some of the earlier experiments when possibly more glyme was used and the reaction temperature was higher, the presence of the

Table IV. Mass Spectra of Cycloadducts[a]

10a (=**10b** = **10c**): *m/e* 152 (23), 137 (14), 109 (10), 97 (9), 96 (54), 95 (40), 91 (9), 81 (100), 68 (9), 67 (16), 65 (7), 57 (7), 56 (14), 55 (15), 53 (15), 44 (10), 43 (13), 41 (20), 39 (27)

11: *m/e* 178, 149, 135, 119, 117, 108, 107, 93, 91

12a (=**12b**): *m/e* 164 (57), 149 (6), 120 (26), 108 (23), 107 (13), 99 (34), 94 (34), 93 (100), 91 (19), 81 (9), 79 (30), 77 (20), 70 (9), 66 (8), 65 (9), 55 (8), 53 (8), 43 (14), 41 (19), 39 (14)

14a (=**14b**): *m/e* 150 (35), 135 (14), 109 (10), 97 (9), 96 (54), 95 (40), 91 (9), 81 (100), 68 (9), 67 (16), 65 (7), 57 (7), 56 (14), 55 (15), 53 (15), 44 (10), 43 (13), 41 (20), 39 (27)

[a] 70-eV mass spectra (rel intensities) recorded on an AEI MS 12 spectrometer. The mass spectra of the other cycloadducts have been described.[7]

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(17) E. LeGoff, *J. Org. Chem.*, **29**, 2048 (1964).

exo,endo epimer **14c** was suggested from high resolution nmr in the region of the sharp methyl doublets of **14a** and **14b** (τ 8.8–9.1). Each of the two doublets appeared to contain a barely resolved further doublet of low intensity similar to those of **10c**. However, this was not investigated further by glc.

In a further experiment the reaction mixture was investigated by nmr for a possible epimerization of **14a** and **14b** under the experimental conditions. While this method was not very accurate, a change in the ratio of **14a**:**14b** was not discernible after 3 days.

Comments on Debromination in Acetone. The major by-product in these reactions was the parent ketone and diacetone alcohol. For example, 2,4-dibromo-2-methyl-3-pentanone (**6b**) and furan afforded the adduct **8** (35%), 2-methyl-3-pentanone (51%), diacetone alcohol (7%), and an unidentified compound (7%). Debromination under rigorously dry conditions using acetone (distilled from (i) $KMnO_4$ and (ii) P_4O_{10}) and furan (refluxed over Na for 30 hr) in a 50:50 mixture (v/v) led to recovery of α,α′-dibromo ketone.

Comments on Debromination in Glyme. Initially, the zinc–copper couple was added in one batch, when it was found that substantial amounts of α,α′-dibromo ketone could be recovered at the end of the reaction. In order to bring about complete debromination it is advantageous to introduce the zinc–copper couple in several portions. Under these conditions the cycloaddition is very efficient and provides a most simple route to seven-membered unsaturated ketones.

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Secondary Deuterium Isotope Effects in Allene Cycloadditions

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Abstract: *Intra*molecular kinetic secondary deuterium isotope effects were obtained for the reactions of allene-*1,1-d_2* with acrylonitrile, 1,1-dichloro-2,2-difluoroethylene, tetracyanoethylene oxide, hexachlorocyclopentadiene, and 5,5-dimethoxytetrachlorocyclopentadiene and for the dimerizations of allene-*1,1-d_2* and 1,2-cyclononadiene-*1-d*. *Inter*molecular effects were obtained for the acrylonitrile and hexachlorocyclopentadiene reactions as well as for the allene dimerization. The results lead to the conclusion that all [2 + 2] cycloaddition processes of allenes, including dimerizations, proceed *via* a multistep pathway, while the [2 + 3] and [2 + 4] cycloadditions proceed *via* concerted mechanisms.

Within the past few years, a surge of general interest in the chemistry of allenic compounds has generated a great deal of mechanistic investigations in the cycloadditions of allenes. A number of kinetic[2] and stereochemical[2b,3] studies are now available, with the stereochemical results seeming to suggest that allene cycloadditions are quite stereoselective. Some observations of stereospecific [2 + 2] cycloadditions led to conclusions that such reactions were multicenter, concerted reactions,[2b] with allene acting in an antarafacial manner similar to the way that ketene has been demonstrated to behave,[4] while most preferred to explain their results on the basis of multistep mechanisms.

We wish to present a rather broad series of studies which seem to support the latter conclusion, and which seem to relegate allene to the category of being just another relatively reactive alkene.[5] In these studies secondary deuterium isotope effects have been utilized as the major mechanistic probe. *Intra*molecular competitive studies provided information about the *product-determining* steps while *inter*molecular competition experiments gave knowledge of the *rate-determining* steps.

A broad spectrum of cycloaddition reactions was investigated: two Diels–Alder reactions ([2 + 4] cycloadditions), the reactions of allene with hexachlorocyclopentadiene (**1**)[6] and with 5,5-dimethoxytetrachlorocyclopentadiene (**2**); one [2 + 3] cycloaddition the 1,3-dipolar cycloaddition of tetracyanoethylene-oxide(**3**) with allene;[7] two [2 + 2] cycloadditions, the reaction of allene with acrylonitrile (**7**)[8] and with, 1,1-dichloro-2,2-difluoroethylene (**9**)[9]; and two dimeriza-

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(1) (a) Taken in part from the Ph.D. dissertation of S.-H. Dai, University of Florida, June 1971; (b) Alfred P. Sloan Foundation Fellow, 1970–1972.

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