dependent contribution to ^{13}C chemical shifts and this may contribute to the observed shift at C4.

Finally, we consider the $^{19}F-^{13}C$ coupling constants observed for those carbons near the $9\alpha F$ group in **2**. A simple interpretation of the Fermi contact contribution to this coupling constant suggests that the value of $J(^{13}C-^{19}F)$ should be roughly proportional to the magnitude of the C2a–F2s bond order element[25,26] since only the s orbitals have finite electron density at the nuclei. Table II lists the coupling constants and bond order elements. At the carbons geminal to the fluorine (C8, C10, and C11), the size of the coupling constants correlates well with the magnitude of the bond order. In the vicinal carbons (C19, C1, C7, C14, C5, and C12),

(25) J. A. Pople, J. W. McIver, Jr., and N. S. Ostlund, *J. Chem. Phys.*, **49**, 2965 (1968), give a more complete theory on how to calculate the Fermi contact contributions to the couplings with finite perturbation theory in the INDO and CNDO approximation.

(26) This approximation is not rigorous, being only strictly applicable in independent electron molecular orbital models. We are also ignoring the differences in the virtual orbital contribution to expression 2.17 in ref 25.

the correlation of the magnitude of J and the bond order elements is also good, the last two carbons (where the F–C 2s bond order is smallest) not showing any observable coupling. A Karplus-type relationship[27] appears to hold for these vicinal $^{13}C-^{19}F$ couplings, the carbon trans to the fluorine ($\phi = 180°$) (C19) showing a much larger coupling than the gauche carbons ($\phi \sim 60°$), C1, C5, C7, C12, and C14.

In summary, we have sought to relate α, β, and γ chemical shifts and $^{19}F-^{13}C$ coupling constants in 9α-cortisol derivatives to the steric and electronic structures we have previously determined for these relatively inflexible molecules. It it clear that current theory is inadequate to account for some of these effects.

(27) M. Karplus, *J. Chem. Phys.*, **30**, 11 (1958).

Cycloadditions of Cyclic Allyl Cations to Furan. Configuration and Conformational Analysis of the Resulting Bridged Six-Membered Rings. Isolation and Identification of Boat and Chair Atropisomers

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Abstract: Debromination of α,α'-dibromocycloalkanones on a column of a modified zinc–copper couple in the presence of furan yields tricyclic adducts at room temperature. The products have been separated, and specific nmr signals and vibrational bands have been assigned to model chair and boat conformers as well as to deformed six-membered rings. Conformational analysis has been applied throughout the paper to correlate the physical properties of the adducts and to rationalize the chemical results. Of the various tricyclics studied the cis diequatorially bridged 16-oxatricyclo[11.2.1.1^{2,12}]heptadec-14-en-17-one ($C_{ee}12$) is interesting in being a conformationally mobile chair, which flips over reversibly into the diaxially bridged boat $B_{aa}12$ ($\Delta G^{\neq} = 16.0$ kcal/mol, $\Delta S^{\neq} = 1.5$ eu, solvent CCl_4). The equilibrium $C_{ee}12 \rightleftharpoons B_{aa}12$ is solvent dependent, the boat being favored in more polar media. In the solid state only the chair conformer $C_{ee}12$ is discernible. Similarly, the tricyclic adduct from 2,13-dibromocyclotridecanone and furan is conformationally mobile, $C_{ee}13 \rightleftharpoons B_{aa}13$. However, the barrier toward interconversion is now substantially lower ($\Delta G^{\neq} < 9$ kcal/mol) and there is a greater bias toward population of the chair. The symmetric tricyclic from 2,11-dibromocycloundecanone and furan exists as the stable boat $B_{aa}11$ which does not show any tendency to spill over into the chair $C_{ee}11$ on heating to 160°. On hydrogenation of the olefinic double bond $B_{aa}11(2H)$ can be isolated, which on heating to 60–80° is converted cleanly and irreversibly into the more stable $C_{ee}11(2H)$ rotamer ($E_a = 26.8 \pm 0.5$ kcal/mol; log $A = 13.6 \pm 0.1$). We have here the first case of the isolation of two compounds differing only in the conformation of the six-membered ring, *i.e.*, of boat and chair atropisomers. Hydrogenation of the mobile pair $C_{ee}12 \rightleftharpoons B_{aa}12$ at room temperature furnishes the six-membered chair $C_{ee}12(2H)$ outright, the boat $B_{aa}12(2H)$ being unstable. As a guide to the conformational analysis of the diverse tricyclics, semiempirical molecular orbital (CNDO/2) calculations have been performed on model bicyclic compounds. On heating and in the presence of acid the tricyclics tend to break up into 2-(2'-furanyl)cycloalkanones. A stereoelectronic effect is proposed to account for the observed range of reactivities. Since the cyclic seven- and eight-membered allyl cations postulated as reactive intermediates must be U shaped, whereas the corresponding 11-, 12-, and 13-membered cations are considered to have largely if not exclusively the W configuration, it may be concluded from the product analysis that the compact mode of cycloaddition is favored over the extended approach by a factor of *ca.* 6:1 with all α,α'-dibromocycloalkanones (except 2,7-dibromocycloheptanone where the ratio is higher). On this basis the transition state of the cycloaddition is suggested to be aromatic and reactant-like.

Debromination of α,α'-dibromo ketones with zinc–copper couple has been shown to yield products,

(1) Ramsay medal recipient, 1972–1973.

the formation of which can be rationalized by postulating allyl cations as reactive intermediates.[2] Al-

(2) (a) H. M. R. Hoffmann, K. E. Clemens, and R. H. Smithers, *J.*

though it may appear to be but a short jump to cyclic allyl cations derived from α,α'-dibromocycloalkanones, a number of preparative and analytical difficulties had to be overcome first of all. The diverse tricyclic adducts obtained by combination with furan and described in the present paper have been found to behave in a fascinating yet comprehensible manner, displaying self-consistent trends on descending the homologous series from large (n = 13, 12) to medium (n = 11, 10, 8) and common rings (n = 7), and again after sterically crowding certain conformers by hydrogenating the olefinic double bond. The reactions to be described yield insight into the ease of formation of cyclic allyl cations and into the mechanism and steric course of the combination with furan.

Nomenclature and Definitions. The various reaction products encountered are outlined in Scheme I and
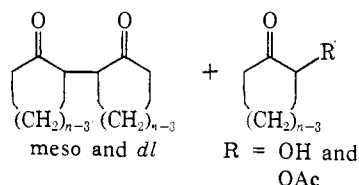
Scheme I. Major Products from the Debromination of α,α'-Dibromocycloalkanones with Zinc–Copper Couple in the Presence of Furan

several stereoisomers   parent cycloalkanone
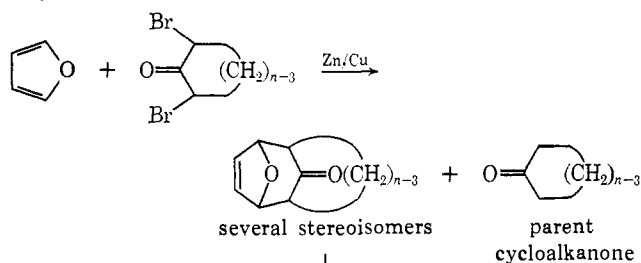
delayed work-up or heat or acidic catalyst

n = 7, 8, 10–13
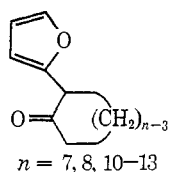
LeGoff zinc–copper couple furnishes further products

meso and dl R = OH and OAc

include tricyclic adduct, parent cycloalkanone, and some other compounds depending on the nature of the zinc–copper couple. As an example of our nomenclature, consider the product of cycloaddition of 2,12-dibromocyclododecanone and furan. According to IUPAC rules the correct name of this compound is 16-oxatricyclo[11.2.1.1^{2,12}]heptadec-14-en-17-one (Scheme I, n = 12). Clearly, the name is not only cumbersome but also fails to define the various stereoisomers. A priori, the tetrahydropyranone moiety can exist in either C for chair or B for boat conformation. Furthermore, the methylene bridge can be attached either equatorially (e) or axially (a). Conformational mobility, which enters for certain methylene chain lengths, introduces further complications.

Following Figure 1 our nomenclature will be self-

Amer. Chem. Soc., **94**, 3940 (1972); (b) H. M. R. Hoffmann, K. E. Clemens, E. A. Schmidt, and R. H. Smithers, ibid., **94**, 3201 (1972); (c) see also H. M. R. Hoffmann, Angew. Chem., Int. Ed. Engl., **12**, 819 (1973), and references cited therein.
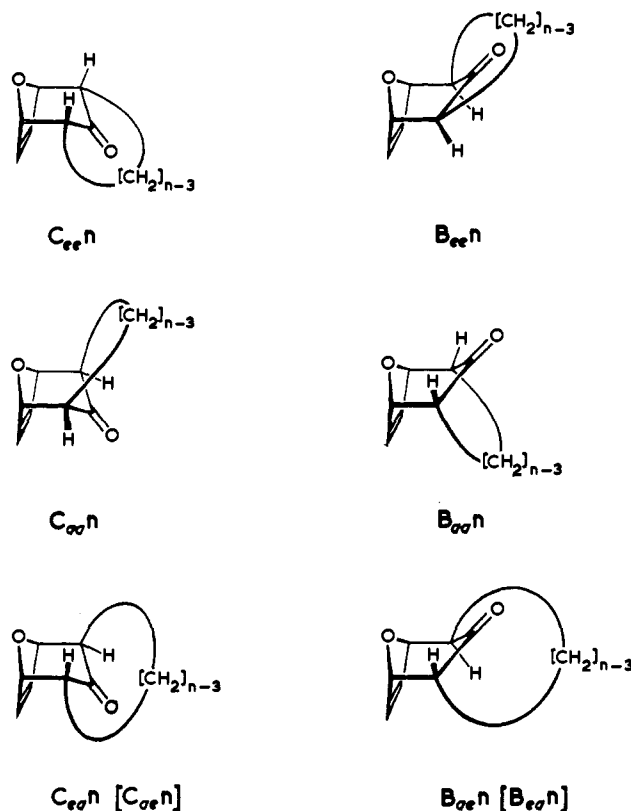
Figure 1. Stereoisomers of 2,4-bridged 8-oxabicyclo[3.2.1]oct-6-en-3-ones.

explanatory. Thus, the tricyclic adduct designated $B_{aa}12$ contains the tetrahydropyranone system as a boat (B), which is bridged cis diaxially (aa) by the methylene chain and is plainly derived from furan and 2,12-dibromocyclododecanone (n = 12). Given an appropriate number (n − 3) of methylene groups three pairs of potential atropisomers ($C_{aa}n \rightleftharpoons B_{ee}n$, $B_{aa}n \rightleftharpoons C_{ee}n$, $C_{ae}n \rightleftharpoons B_{ea}n$) can be envisaged a priori, each component of the last pair being asymmetric and existing as a dl pair. We shall show that compounds of the $C_{aa}n$, $B_{aa}n$, $C_{ee}n$, and $C_{ae}n$ class can be isolated individually or "frozen" on the nmr time scale. The conformationally isomeric $B_{ae}n$ and $B_{ee}n$ tricyclics are probably formed as well or arise as transient species.

Table I. Coupling Constants for $C_{aa}n$, $C_{ee}n$, and $B_{aa}n$ Tricyclics (Solvent CCl₄, 25°)[a]

Tricyclic compd	J_{mb},[b] Hz	Tricyclic compd	J_{mb}, Hz
$C_{aa}7$	<0.4	$C_{ee}12$	3.5[c]
$C_{aa}8$	<0.4	$B_{aa}7$	8.5
$C_{aa}10$	<0.4	$B_{aa}8$	8.0
$C_{aa}11$	<0.4	$B_{aa}11$	7.5
$C_{aa}12$	<0.4	$B_{aa}12$	7.5
$C_{aa}13$	<0.4		

[a] $J_{aa'}$ and J_{ab} are small or negligible for symmetrical tricyclics but not so for $C_{ae}n$ (see Table II). [b] With increasing n in $C_{aa}n$ the peak height of the bridgehead singlet increases to approach that of the olefinic singlet, suggestive of weak coupling ($J_{mb} < 0.4$ Hz), which becomes progressively weaker. [c] At −5°.

Table II. Chemical Shifts and Coupling Constants of the Series $C_{ae}n$ ($n = 10-12$)[a]

n	Olefinic protons, ppm		Bridgehead protons,[b] ppm		Obsd separation of olefinic signals, Hz	$J_{aa'}$, Hz	$J_{ab},J_{a'b'}$, Hz	J_{mb}, Hz	$J_{m'b'}$, Hz
	a	a'	b	b'					
10	6.05	6.11	4.60	4.61	1.4/4.5/1.4/1.5/1.4/4.5/1.4	5.9	1.7	~ 0	~ 3
11	6.06	6.13	4.61	4.58	1.5/4.5/1.5/2.0/1.5/4.5/1.5	6.1	1.7	~ 0	~ 3
12	6.08	6.16	4.60	4.56	1.5/4.7/1.5/2.7/1.5/4.7/1.5	6.3	1.7	~ 0	~ 3

[a] Data refined by LAOCOON III; see S. M. Castellano and A. A. Bothner-By, *J. Chem. Phys.*, **41**, 3863 (1964). [b] Bridgehead proton b is vicinal to equatorial methine proton m; proton b' is vicinal to axial proton m'.
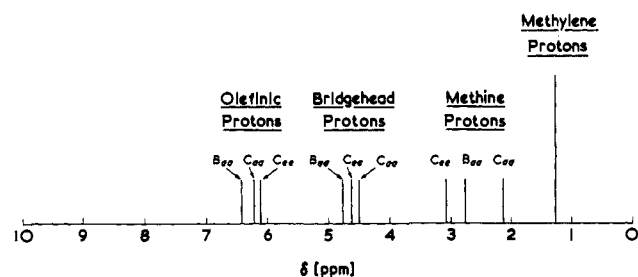

Figure 2. Typical chemical shifts in constrained B_{aa}, C_{aa}, and C_{ee} tricyclics [$C_{ae}n$ compounds show olefinic protons at δ 6.1, bridgehead protons at δ 4.6, and two methine resonances at >3.0 (axial) and <2.3 (equatorial)].

Configurational and Conformational Assignments. Since some of the tricyclics were fairly sensitive and tended to epimerize or break up under the reaction conditions, it was above all necessary to take care in their isolation and purification. Interestingly, slow crystallization and hand picking of crystals were in certain cases superior to chromatography as a separation technique, for instance in the isolation of pure $C_{ee}12 \rightleftharpoons B_{aa}12$.

Our structural assignments rest on a series of independent tests and observations. Thanks to the presence of the bridging oxygen the pmr spectra were well resolved and clearly revealed coupling constants (Tables I and II). Where applicable (Table III and Figure 2)

Table III. Pmr Chemical Shifts,[a] δ (TMS, CCl$_4$), of Tricyclics at 25°

Tricyclic compd	Olefinic protons	Bridge-head protons	Equatorial protons	Axial protons
$C_{aa}7$	6.22	4.60	2.38	
$C_{aa}8$	6.22	4.60	2.10	
$C_{aa}11$	6.14	4.54	2.12	
$C_{aa}12$	6.16	4.62	2.16	
$C_{aa}13$	6.20	4.66	2.18	
$B_{aa}7$	6.50	4.84		3.16
$B_{aa}8$	6.44	4.76		2.84
$B_{aa}11$	6.38	4.74		2.78
$B_{aa}12$[b]	6.38	4.82		2.78
$C_{ae}10$	6.08	4.60	2.28	3.92
$C_{ae}11$	6.10	4.59	2.22	3.40
$C_{ae}12$	6.12	4.58	2.10	3.28
$C_{ee}12$[b]	6.10	4.76	3.32	
$C_{ee}13 \rightleftharpoons B_{aa}13$[c]	6.20	4.74	2.98	

[a] All pmr spectra are reproduced individually in ref 8. [b] Chemical shifts are temperature dependent, recorded at 0°. [c] Recorded in CDCl$_3$.

pmr assignments were corroborated by decoupling experiments, while solvent and temperature dependent spectra (Table X and Figure 7) were helpful in elucidat-

Table IV. Ir Carbonyl Stretch Frequencies (cm^{-1}) of Tricyclics and Selected Reduced Tricyclics[a]

n	$C_{aa}n$	$B_{aa}n$	$C_{ae}n$	$C_{ee}n$
7	1710	1721		
8	1705	1711 br		
10			1711 br	
11	1703	1703	1714	
12	1703	1704	1713	1714
13	1703	1704 sh	1711	1714

n	$C_{aa}n(2H)$	$B_{aa}n(2H)$	$C_{ae}n(2H)$	$C_{ee}n(2H)$
7	1710	1720		
8	1707			
11	1703	1703	1705	1711
12	1703			1713
13		1703 sh[b]		1711[b]

[a] All spectra were recorded in CCl$_4$ solvent with reference to polystyrene at 1603 cm^{-1} and were expanded such that 1 cm was equivalent to 20 cm^{-1}; error ± 2 cm^{-1}. [b] Tentative results.

ing conformational mobility. Ir spectra (Table IV) brought to light further structural subtleties (Figure 6a–c) as well as analogies. Dipole moment measurements of conformationally rigid and mobile systems were especially instructive and demonstrated independently the enhanced polar character of boat *vis-à-vis* chair derivatives (Table V). More or less polar character was qualitatively manifest in R_f values; solubilities and even melting points (Table VII) were useful for a preliminary classification. A full glc analysis was carried out on the hydrogenated reaction mixtures and the observed relative retention times were helpful in identification. The key tricyclics were submitted to C and H as well as mass spectroscopic analysis. The collated information allowed us to assign structures without recourse to preconceived mechanistic or conformational notions.

Conformation and Deformation from Experimental Data. 1. $C_{aa}n$ Series. On steric grounds the introduction of two syn-axial methylene groupings into a saturated six-membered ring is not favorable. Syn-diaxial and especially transannular repulsion will be aggravated further when the methylene loop is part of a medium or large ring ($n \geq 8$). The only way of relieving steric compression is by moving the methylene groups apart; however, as a consequence partial flattening of the six-membered ring can hardly be avoided.

Now the vicinal coupling constant is very small or negligible in the $C_{aa}n$ series ($J_{mb} < 0.4$ Hz, *cf.* Table I). For comparison, the analogous coupling in the parent 8-oxabicyclo[3.2.1]oct-6-en-3-one is known to amount to ~ 1.5 Hz, whereas coupling of the axial and the bridgehead proton is larger, being 5 Hz, despite the similar torsional angle ($\sim 60°$, *cf.* Figures 3 and 4).

Clearly, the electronegative oxygen which is anti-

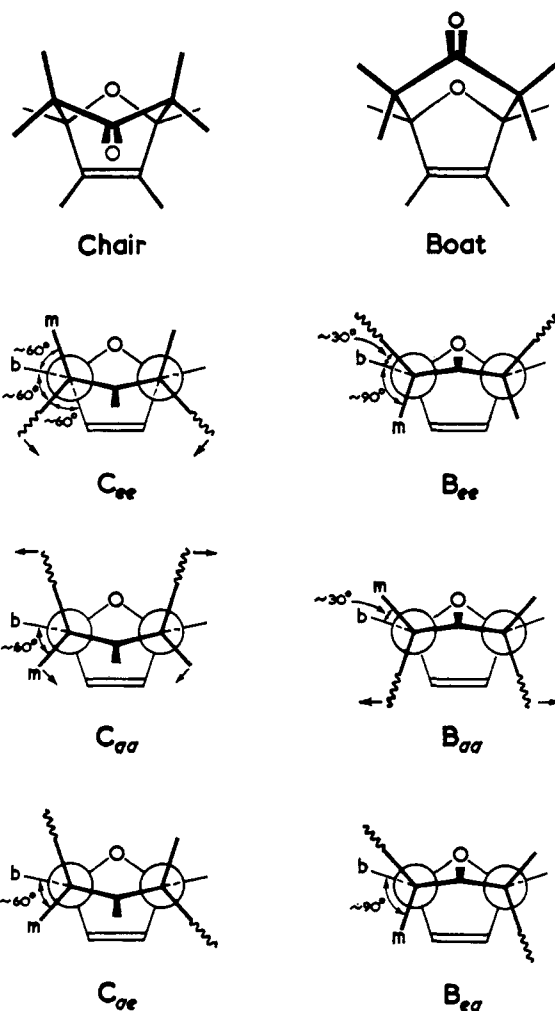Figure 4. Vicinal coupling in 8-oxabicyclo[3.2.1]oct-6-en-3-one.[4]

$$J_{H^{ee},H^b} \leqslant 1.5 \text{ Hz}$$
$$J_{H^{ea},H^b} = 5 \text{ Hz}$$

Chair   **Boat**

C_{ee} B_{ee}

C_{aa} B_{aa}

C_{ae} B_{ea}

Figure 3. Torsional angles of tricyclic chair and boat derivates.

repulsion

Figure 5. Postulated dipole–dipole repulsion in a boat tetrahydropyranone.

Table V. Dipole Moments of Selected Tricyclics[a]

Tricyclic	Dipole moment, D	Error, ±D
$C_{aa}7$	1.9	0.2
$C_{aa}12$	1.7	0.15
$C_{ee}12(2H)$	1.5	0.15
$B_{aa}11$	2.9	0.2
$C_{ee}12 \rightleftharpoons B_{aa}12$	2.4	0.15
$C_{ee}13 \rightleftharpoons B_{aa}13$	2.3	0.25

[a] All results were averaged from several separate readings at different concentrations in solvent benzene.

periplanar to the equatorial proton reduces vicinal coupling of that proton and in $C_{aa}n$ more so than in the parent bicyclic. Since the six-membered chair in $C_{aa}n$ ($n \geq 8$) is considered to have flattened, the torsional angle controlling J_{mb} will come closer to 90°, when J_{mb} ~ 0 Hz, as indeed observed (Table I, footnote b).

It is worthy of note that the carbonyl stretch frequencies of $C_{aa}n$ (Table IV) are lower than the range observed for ordinary cyclohexanones (1709–1714 cm^{-1}), especially for $n \geq 8$. Since the postulated deformation of the six-membered ring toward a half-boat with five atoms in one plane should expand the internal C–CO–C angle, it is at once understandable that the $C_{aa}n$ carbonyl absorption ($n \geq 8$) is shifted to shorter wave numbers with respect to a conventional, i.e., strainless, cyclohexanone derivative.

As regards other physical properties $C_{aa}n$ derivatives melt higher than any of the other C and B isomers (Table VII). This finding is consistent with a low entropy of fusion or a relatively rigid conformation in the liquid state. As expected, $C_{aa}n$ tricyclics have low dipole moments (Table V), and they also tended to be relatively stable to heating in that they showed little tendency toward cleavage into 2-(2'-furanyl)cycloalkanones, unlike the other isomers (cf. Scheme I and discussion below).

2. The $B_{aa}n$ Series. The boat conformer of cyclohexane is about 6 kcal/mol above the chair and ener-
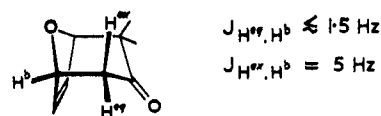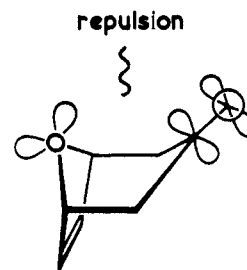
getically unfavorable because of (a) two eclipsed ethanoid arrangements and (b) transannular repulsion of the two flagpole hydrogen atoms.[3] Basically, our bridged tetrahydropyranone boats suffer from the same conformational impediments, except that (b) is absent and presumably replaced by somewhat less severe dipole–dipole repulsions (see Figure 5 and discussions of CNDO/2 calculations below).

The vicinal coupling constant J_{mb} can be seen to drop from 8.5 Hz in $B_{aa}7$ to 7.5 Hz in $B_{aa}11$ and $B_{aa}12$ (Table I). Clearly, as the methylene bracket becomes looser, the torsional angle controlling J_{mb} increases and as a consequence J_{mb} drops by 1 Hz altogether (Figure 3). Put another way, with increasing chain length the boat conformer appears to adjust its geometry by partial flattening. In so doing several advantages accrue. First of all, dipole–dipole repulsion is expected to recede; further, the eclipsing interaction within the pair of ethanoid groupings is reduced and, finally, nonbonding repulsion of the syn-diaxial methylene groupings attached to the boat will be alleviated. Our interpretation of the trend in J_{mb} is supported by the pattern of the ir carbonyl absorption (Table IV). Thus, for $B_{aa}7$ repulsion of the dipoles associated with the two oxygen atoms (Figure 5) is expected to be most severe. Further, the internal C–CO–C angle will also be smallest in this tricyclic and on both grounds carbonyl stretching will require the greatest amount of energy. Once we have ascended the series to reach $B_{aa}11$ and $B_{aa}12$, the six-membered boat appears to have flattened to its limit in that the carbonyl stretching frequency has

(3) Cf. E. L. Eliel, N. A. Allinger, S. J. Angyal, and G. A. Morrison, "Conformational Analysis," Interscience, New York, N. Y., 1965.

dropped to 1704 cm^{-1} and then stays constant, as is consistent with the trend in vicinal coupling constants J_{mb}. Thus $B_{aa}n$, like $C_{aa}n$, seems to flatten with increasing number of methylene groups, and in both series of conformers the ir carbonyl stretch frequency can be seen to reach the limiting low value of 1704 cm^{-1} for $n = 11$.

As expected $B_{aa}n$ derivatives have marked dipole moments (Table V). The comparatively low-field position of the bridgehead and olefinic protons in the nmr (Figure 2) accords with the view that as a class of tricyclics $B_{aa}n$ are quite strained and polar.

3. $C_{ae}n$, $B_{ae}n$, and $B_{ee}n$ Derivatives. Space-filling models suggest that $C_{ae}n$ compounds might exist without undue strain or offensive transannular repulsion from about $n = 10$ onwards. After having prepared $C_{ae}10$, $C_{ae}11$, and $C_{ae}12$ we did indeed find that their ir carbonyl absorptions were normal (Table IV), although the carbonyl peak for the first member $C_{ae}10$ appeared as a broad band suggesting some conformational ambiguities. Furthermore, the axial proton α to the carbonyl group in $C_{ae}10$ was found to be markedly deshielded (δ 3.92 ppm), indicative of some distortion of the six-membered chair and/or van der Waals repulsion. Most importantly, coupling of the axial methine proton with the bridgehead proton amounted to only 3 Hz, even for $C_{ae}12$ (see Table II). Hence, a torsional angle $>60°$ and an asymmetric deformation of the six-membered chair seem likely.

The existence of $B_{ae}n$ and $B_{ee}n$ compounds is less well established. $B_{ae}n$ derivatives of large rings should turn into $C_{ae}n$ tricyclics. However, $B_{ae}10$ which would *not* be expected to flip over readily into $C_{ae}10$ is possibly formed as the minor isomer in the reaction of furan with *trans*-2,10-dibromocyclodecanone. $B_{ee}12$, $B_{ee}13$, and $B_{ee}11$ are considered to be transient species before irreversibly turning into the observed tricyclics $C_{aa}12$, $C_{aa}13$, and $C_{aa}11$, respectively (see discussion below).

4. $C_{ee}n$ and Conformational Mobility. Isolation and Identification of Six-Membered Boat and Chair Atropisomers. On considering with Dreiding models the torsional angle of each of the cis-diequatorial methylene groupings with the carbonyl group, one might be tempted to assume that the methylene chain in $C_{ee}12$ extends *below* the face of the carbonyl moiety. However, space-filling models show quite clearly that this cannot be so as long as the six-membered ring is a chair. Thus, whereas the cis-diequatorial methylene groups are nearly eclipsed with the carbonyl double bond, the rest of the puckered methylene chain screens the carbonyl oxygen rather firmly from the exo face of the molecule. In this way new rules are imposed on the conformation of the 12-membered ring and these constraints are eventually relayed to the six-membered chair. As an illustration of this point, consider the vicinal coupling constant for $C_{ee}12$, which is $J_{mb} = 3.5$ Hz, in contrast to 5 Hz observed for both the parent 8-oxabicyclo[3.2.1]oct-6-en-3-one (Figure 4) and its cis-diequatorial 2,4-dimethylated homolog.[2a,4] Thus, the torsional angle controlling J_{mb} has increased, as is consistent with our view that the six-membered chair in $C_{ee}12$ is pinched by the methylene chain from the exo but not the endo face. Further, the syn-diaxial protons

of $C_{ee}12$ resonate 0.65 ppm further downfield than those of the cis-diequatorial 2,4-dimethyl-8-oxabicyclo[3.2.1]-oct-6-en-3-one, suggestive of some strain and van der Waals repulsion. Finally, whereas the carbonyl group of cyclododecanone itself prefers an angle of *ca.* 80° with respect to the average ring plane,[5] the carbonyl grouping of $C_{ee}12$, its neighboring methine, together with the cis-diequatorial methylene carbons, are forced into a roughly coplanar W arrangement. Thus, the remaining loop of seven methylene groupings crowds the carbonyl group heavily, presses it down, and in doing so forces the six-membered ring into a conformation which we propose to name *superchair* (see also Figure 9 and discussion below). A recoil from this wound up conformation is only possible by populating the boat $B_{aa}12$, in which the 12-membered ring may unfold and relieve nonbonded interactions.

As expected from the dipole moment measurements (Table V) the equilibrium $C_{ee}12 \rightleftharpoons B_{aa}12$ is solvent dependent, $C_{ee}12$ being favored marginally in CCl$_4$, whereas $B_{aa}12$ is stabilized by 600 cal/mol in more polar solvents such as CDCl$_3$ and (CD$_3$)$_2$CO. In fact, the relative population of the boat $B_{aa}12$ as a function of the solvent (Table X) could be exploited as a criterion of solvent polarity, should there be any interest in obtaining another empirical parameter.

The equilibrium $C_{ee}12 \rightleftharpoons B_{aa}12$ could be frozen out on the nmr time scale by cooling to 0° (*cf.* also Figure 1 in ref 6). A complete line-shape analysis of the olefinic resonance in solvent CCl$_4$ and (CD$_3$)$_2$CO over the range of full resolution to coalescence (-5 to 60°) revealed a free energy of activation $\Delta G^{\ddagger} = 16.0$ and 15.8 kcal/mol and $\Delta S^{\ddagger} = 1.5$ eu ($\pm 50\%$), respectively. The Arrhenius parameters were $E_a = 17.3$ kcal/mol and log $A = 13.7$.

In the detection of equilibria of species with low barriers to interconversion, it is often instructive to change the time scale and use other forms of spectroscopy with higher frequencies of radiation such that individual species are observed superposed on each other rather than a weighted mean of their spectra as may be the case in nmr spectroscopy. The ir spectrum of $C_{ee}12 \rightleftharpoons B_{aa}12$ in CCl$_4$ at room temperature (Figure 6a) does indeed reveal two carbonyl peaks at 1714 and 1704 cm^{-1} which can be assigned to the chair and boat, respectively.

It is worthy of mention that in the solid state $B_{aa}12$ was no longer discernible as judged by the ir spectrum of the mulled material which displayed only the carbonyl stretching frequency at 1713 cm^{-1} characteristic of $C_{ee}12$ (see Figure 6b). Interestingly, the =CH stretch frequency of $C_{ee}12$ at 3090 cm^{-1} in the solid state (Figure 6b) is much more intense than that of the dissolved material (Figure 6a) or of $C_{aa}12$. Possibly, in the crystal the HC=CH bond is distorted asymmetrically with respect to the plane of symmetry of the molecule such that =CH stretching is dipole enhanced. If this interpretation is correct, $C_{ee}12$ should oscillate between two asymmetric conformations. In any event, one should be able to determine the structure of solid $C_{ee}12$ more precisely by X-ray crystallography. Our findings serve as a clear warning that the conformation of a polar molecule can change considerably with the medium.

(4) A. E. Hill, G. Greenwood, and H. M. R. Hoffmann, *J. Amer. Chem. Soc.*, **95**, 1338 (1973).

(5) J. Dehli and P. Groth, *Acta Chem. Scand.*, **23**, 587 (1969).

(6) J. G. Vinter and H. M. R. Hoffmann, *J. Amer. Chem. Soc.*, **95**, 3051 (1973).
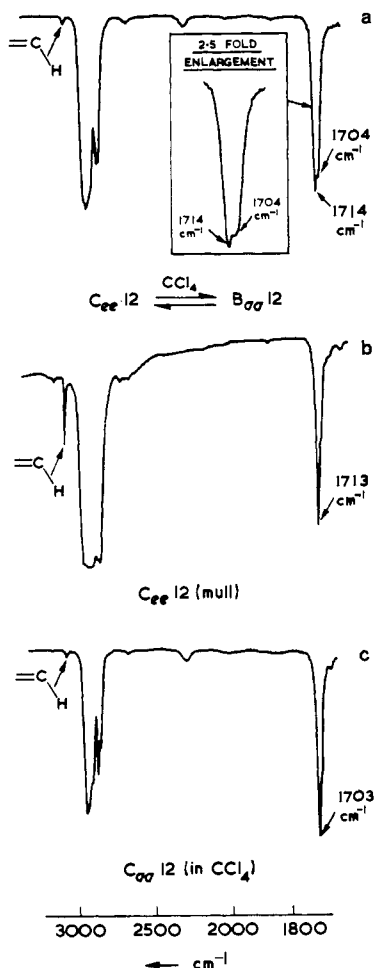
Figure 6. Ir spectra of selected tricyclics.

Figure 7. Pmr spectra of $C_{ee}13 \rightleftharpoons B_{aa}13$ at 25° and of $C_{ee}12 \rightleftharpoons B_{aa}12$ at 100°.

Figure 8. Postulated steric repulsion in $B_{aa}n(2H)$.

The equilibrium of the next higher homologs $C_{ee}13 \rightleftharpoons B_{aa}13$ could no longer be frozen out on the nmr time scale at $-80°$, the material crystallizing from $CFCl_3$ at this temperature ($\Delta G^{\ddagger} < 9$ kcal/mol). Even the ir carbonyl bands appeared to be poorly resolved. Indeed, without the auxiliary information from the other tricyclics it would have been very easy to misinterpret the pmr spectrum of $C_{ee}13 \rightleftharpoons B_{aa}13$ (Figure 7) and to overlook conformational mobility altogether. However, the dipole moment measurements (Table V), the solvent dependence of the coupling constant J_{mb}, and the similarity of the nmr spectrum to that of $C_{ee}12 \rightleftharpoons B_{aa}12$ at 100° (Figure 7) leave little doubt that $C_{ee}13$ spills over into $B_{aa}13$, although less so than its lower homolog. From the change of coupling constant J_{mb} with solvent the population of $C_{ee}13$ at room temperature has been calculated to be 73 ± 10% in $(CD_3)_2CO$ and $CDCl_3$ and 87 ± 13% in the less polar solvent CCl_4.

We have found no evidence for an equilibrium between $C_{ee}11$ and $B_{aa}11$. However, it seems likely that $C_{ee}11$ (or a stretched form of it) is formed initially via a W cation and then flips irreversibly (>95% by nmr) into the isolated conformer $B_{aa}11$ (see below). The breakup of $B_{aa}11$ into the corresponding furano ketone might also proceed via $C_{ee}11$ as reactive intermediate.

Hydrogenated Tricyclics. Many of the tricyclics, especially the more polar and strained ones, were sensitive to heat and acid. Hydrogenation of the olefinic double bond provided an acceptable and straightforward means of stabilizing the adducts and of sub-
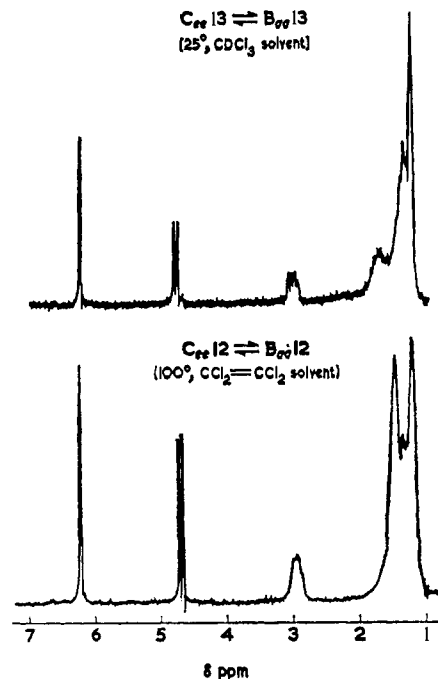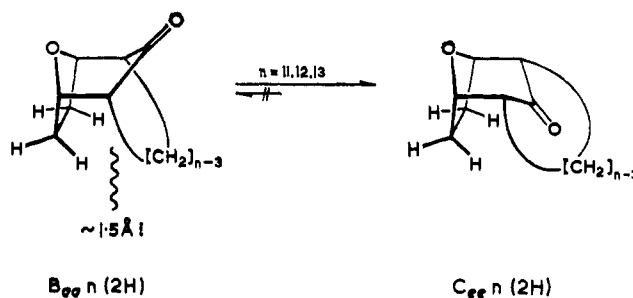
mitting them to glc analysis. In the course of this work further conformational contours came to light.

Thus, hydrogenation of $C_{aa}n$ to $C_{aa}n(2H)$ ($n = 7$, 8, 11–13) did not within experimental error change the ir carbonyl stretch frequency (Table IV) and a conformational flip into $B_{ee}n(2H)$ ($n = 7$–13) was not observed nor expected. On hydrogenating the mixture $C_{ee}12 \rightleftharpoons B_{aa}12$ all conformational flexibility was lost and $C_{ee}12$-(2H) was shown to be the only conformer to exist at amenable temperatures.

Why is $B_{aa}12(2H)$ unstable relative to $C_{ee}12(2H)$? Models show that nonbonded repulsion and eclipsing of the newly acquired ethano grouping and the syn-diaxial chain are severe, especially so since the ethano bridge is held rigidly, its two inside hydrogens having no chance of rotating away from the neighboring methylene groupings (Figure 8). In point of fact, the release of strain on forming $C_{ee}12(2H)$ has been calculated to be worth 40 kcal/mol. While this value is probably an overestimate, there can be little doubt that $B_{aa}12(2H)$ is very much destabilized.

Not surprisingly, hydrogenation of the homologous pair ($n = 13$) afforded $C_{ee}13(2H)$ and again no boat conformer; in this instance, the methylene loop is even looser and the chair should exist without conformational

difficulties. In this context, hydrogenation of $B_{aa}11$ which stayed conformationally rigid at room temperature was of some interest. At room temperature the pmr signals of the reduced product could be assigned unequivocally to the stable six-membered boat $B_{aa}11$-(2H), there being no evidence for the presence of any chair conformer (see Tables IV and XI). However, on keeping $B_{aa}11(2H)$ in hexachlorobutadiene at 60–80°, a clean and total conversion into $C_{ee}11(2H)$ occurred over a period of 20–100 min (E_a = 26.8 ± 0.5 kcal/mol, log A = 13.6 ± 0.1) and continued heating to 160° did not regenerate any boat conformer. Put another way, we have here the first example of the isolation of two compounds which differ only in the conformation of the six-membered ring or, more precisely, are boat and chair atropisomers. At the same time it is clear that an eight-membered methylene bridge is capable of spanning the cis-diequatorial positions of the six-membered cyclohexanone-like chair. This observation will be useful when discussing possible mechanisms of cycloadditions and in particular the formation of $B_{aa}11$ from an intermediate allyl cation with W geometry.

Conformation and Deformation from CNDO/2 Calculations. As a guide to some of the experiments and their interpretation and in order to gain physical insight into the dynamic behavior of $C_{ee}12$ we have performed semiempirical molecular orbital calculations (CNDO/2)[7] on the parent 8-oxabicyclo[3.2.1]oct-6-en-3-one, the saturated 8-oxabicyclo[3.2.1]octan-3-one, as well as on the 2,4-dimethyl analogs. Each molecule was set up in a Cartesian framework to obtain atomic coordinates compatible with accepted bond lengths and bond angles. The final molecular parameters were adjusted by CNDO/2 utilizing the variation principle.[8] The following conclusions are worth noting.

1. Dipole moments were found consistently around 0.9 D for the six-membered chair and 3.5 D for the boat arrangement, whether the compounds were 2,4-dimethylated or not. Experimentally determined dipole moments for bona fide chair and boat derivatives (Table V) are in encouraging agreement with calculated values and leave no doubt about our conformational assignments.

2. Expansion of the internal C–CO–C angle of an 8-oxabicyclo[3.2.1]oct-6-en-3-one, either in the parent or substituted or in its hydrogenated form, is predicted to be energetically favorable, especially for six-membered chair conformations. The described deformation of the bond angles—which of course are not rigid—always causes a decrease in the overlap population of the carbonyl bond and hence one expects a decrease in ir carbonyl stretch frequency. It has been found experimentally that methylation of the parent bicyclic α to the carbonyl group lowers the carbonyl frequency.[2a,4] Presumably, an expansion of the internal C–CO–C angle (and also some flattening of the chair) creates more favorable torsional angles[3] in this case.

3. Flattening of the six-membered ring toward a half-boat with five atoms in one plane is calculated to be energetically more costly and it is interesting to note that given stiff bond angles, this process is actually pre-

dicted to cause an *increase* in carbonyl frequency. Thus, in the real life situation angular deformation and flattening are likely to be combined. Flattening should also be more facile in some of the crowded cis-diaxial chair and boat derivatives when relief of strain becomes mandatory.

4. The overlap population of the carbonyl bond in a constrained boat as in $B_{aa}7$ (but not for $n \geq 8$) has been calculated to be higher than that of an undistorted chair, in accord with experimental findings (Table IV). Furthermore, classical dipole–dipole repulsion across the carbonyl oxygen and the ether oxygen (Figure 5) is estimated to raise the energy of the boat by 0.4 kcal/mol. Apparently, by minimizing this very repulsion the constrained boat $B_{aa}7$ acquires a stronger carbonyl bond.

5. The population analysis suggests that hydrogenation of the olefinic double bond in 8-oxabicyclo[3.2.1]-oct-6-en-3-one leads to an increase in carbonyl bond strength, but has little, if any, effect on the corresponding frequencies in the diequatorially disposed 2,4-dimethyl derivatives.

It is of interest that the ir carbonyl frequency of the unsaturated parent bicyclic is indeed lower (1720 cm^{-1}) than that of its hydrogenated form (1725 cm^{-1});[4] while loss of π–π overlap on reduction could be invoked it must be remembered that $C_{aa}n$ and the corresponding $C_{aa}n(2H)$ derivatives show their respective carbonyl band at the same frequency within experimental error (cf. Table IV). Presumably, π–π overlap is not very marked and lost easily on 2,4 substitution. Photoelectron spectroscopy could be informative in further investigations.

In conclusion, there exists a broad spectrum of chair and boat conformers and it appears that we may manipulate almost at will the shape of the six-membered ring by the simple device of bridging the α,α'-carbonyl positions.

Formation of 2-(2'-Furanyl)cycloalkanones. In general 8-oxabicyclo[3.2.1]oct-6-en-3-ones including the parent compound[4] are sensitive toward heat and are cleaved to 2-(2'-furanyl) ketones (cf. Scheme I). The same transformation may be brought about under milder conditions with acidic catalysts, e.g., on treatment with a solution of $ZnBr_2$ in methanol or anhydrous HCl in ether.

In investigating the formation of furanylated cycloalkanones as a possible secondary reaction we have found that the tricyclic precursors show a remarkable range of reactivities. Thus, as a class of compounds $C_{aa}n$ were relatively inert toward heat and acid. For example, $C_{aa}7$ completely survived heating to 100° for 8 hr and $C_{aa}12$ remained unchanged at 70° after 100 hr. Under the same conditions (70°, 100 hr) mixed crystals of $C_{ee}12 \rightleftharpoons B_{aa}12$ and $C_{aa}12$ produced a reddish oil with the appearance of pmr peaks due to 2-(2'-furanyl)-cyclododecanone; again $C_{aa}12$ showed no change.

Interestingly, 2.13-dibromocyclotridecanone (which most nearly resembles the most simple disecondary system, viz. 2,4-dibromo-3-pentanone) behaved like its acyclic counterpart by not entering into any α-substitution during reaction with furan. Hence, one might expect that $C_{ee}13 \rightleftharpoons B_{aa}13$ is more stable toward cleavage and, indeed, the system required 6 hr at 100° for breakup. Finally, $B_{aa}11$ was quite stable on its own,

(7) J. A. Pople and D. L. Beveridge, "Approximate Molecular Orbital Theory," McGraw-Hill, New York, N. Y., 1970.

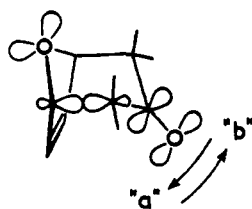(8) J. G. Vinter, Ph.D. Thesis, London, 1973.

Figure 9. Deformation of the six-membered ring into superchair (cis-diequatorial pinching from exo face; carbonyl motion downwards, "a") and toward a half-boat (syn-diaxial repulsion of methlene chain; carbonyl motion upwards, "b").

Figure 10. Cyclic allyl cations with U and W configuration.

but in the presence of ethereal hydrogen chloride it fragmented slowly at room temperature over 24 hr, and quickly at 150° over 10 min under the same conditions.

How can we rationalize these contrasting reactivities? Although the experimental evidence is not complete, we suggest that orbital alignment of the breaking σ bond with the carbonyl π system is critical. Consider $C_{ee}12$ as an example. By virtue of the strained superchair conformation both σ bond and carbonyl π orbital are nearly parallel and hence cleavage of the σ bond with concomitant gain of enolate resonance should ensue readily. Consistently, $C_{ee}13$, which has the looser cis-diequatorial chain, is thermally more stable. By extrapolation, $C_{ee}11$ should be expected to break up most easily, cis-diequatorial pinching being most severe. While $C_{ee}11$ has never actually been detected by nmr up to 150°, it is conceivable that the cleavage of the flattened boat $B_{aa}11$ at 150° in the presence of hydrogen chloride comes about by squeezing the molecule through a low equilibrium concentration of the $C_{ee}11$ conformer which then fragments readily.

As regards the marked thermal stability of the $C_{aa}n$ tricyclics, it will be seen that flattening of the six-membered chair toward a half-boat (arrow "b" in Figure 9) *impedes* incipient enolate resonance and hence cleavage of the molecule.

Altogether, it seems clear that the postulated deformation effects can account satisfactorily for the properties of the various tricyclics. From an experimental and conformational viewpoint the deformation into the superchair (arrow "a" in Figure 9) is perhaps most interesting and novel.

Mechanism and Stereochemistry. Let us assume to begin with that the symmetrical tricyclics, *i.e.*, $C_{aa}n$, $C_{ee}n$, and $B_{aa}n$, are formed in concerted fashion. In order to distinguish the compact boat-like[9] transition state from the extended chair[9] alternative we must know the configuration of the intermediate allyl cation (and, of course, that of the tricyclic adducts). In the case of the seven- and eight-membered cation the situation is clear-cut since the U configuration is sterically enforced (Figure 10). Hence, the product ratio $C_{aa}n/B_{aa}n$ immediately reveals the competition of the two paths. Can we draw any conclusions about the configuration of 11-, 12-, and 13-membered allyl cations? *A priori*, one may consider the reactive intermediates to be (i) U shaped, (ii) W shaped, or (iii) partly U, partly W shaped. Further, there exists a slight margin for error, because it is not clear whether certain $C_{ae}n$ adducts (which are formed in small quantities only) are primary or epimerization products; also, in special

(9) The terms boat and chair refer to the formation of the seven-membered ring; see also ref 2c.
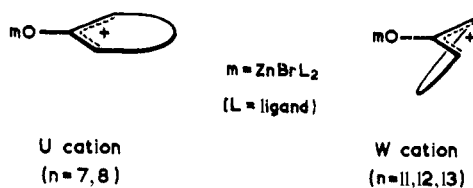
cases a small amount of tricyclic adduct might disappear and be converted into furanylated cycloalkanone. Having raised these possible objections we believe that our results can none the less be interpreted in a simple and self-consistent way. Space-filling models suggest that a U cation derived from a large ring ($n = 11$–13) will suffer from transannular repulsion, especially of the methylene groups attached to the allylic termini. In contrast, W cations appear to be relatively strainless for $n = 11$–13, and the oxygen of the cation is never completely inside the ring but, together with the postulated π-allyl system, at an angle of *ca.* 90° to the rest of the molecule (Figure 10). In this way, molecular packing is quite efficient and the zinc moiety of the proposed zinc oxyallyl intermediate is not in any way encumbered sterically. However, it appears that one of the two faces of the allyl cation is completely screened from nucleophilic attack by the methylene chain, not unlike the situation in a bicyclic. Hence, the actual cycloaddition to furan might well proceed with "retention of configuration," *i.e.*, by front-side collapse of a furan-separated ion pair.[10]

In postulating the exclusive formation of W cations (aside perhaps from some sickle cation) for $n = 11$–13 the following general points should be borne in mind.

(i) From $n = 11$ onwards the yields of tricyclic adducts increase (Table VI); *i.e.*, on leaving behind medium rings the ease of formation of the postulated intermediate allyl cations appears to increase.

(ii) *cis*-Cycloalkenes are more stable than their trans isomers for $n \leq 10$, but *trans*-cycloundecene and *trans*-cyclododecene are more stable than the corresponding cis isomers.[11]

(iii) The most simple acyclic disecondary dibromo ketone, *viz.* 2,4-dibromo-3-pentanone, is free to rotate; on equilibration it gives a *meso/dl* ratio which approaches that of the 11- and, more so, of the 12-membered α,α'-dibromocycloalkanones;[12] with zinc–copper couple it forms a W cation which combines with furan, the compact/extended ratio being *ca.* 8:1.[2a]

(iv) $B_{aa}n$ derivatives ($n = 11$–13) must necessarily arise from $C_{ee}n$ by a conformational flip. While $C_{ee}11$ has not been detected by nmr [whereas $B_{aa}11(2H) \overset{60-80°}{\rightleftharpoons} C_{ee}11(2H)$], the equilibria $C_{ee}n \rightleftharpoons B_{aa}n$ ($n = 12, 13$) have already been discussed.

(v) $C_{aa}n$ tricyclics must be formed from nonisolable $B_{ee}n$ derivatives ($n = 11$–13) by a unidirectional flip.

Based on these premises the ratio of compact *vs.* extended transition state can be derived from the product analyses (Table VI). One can see that the ratio is about constant $((6 \pm 1):1)$ for all cycloadditions except that

(10) See also R. A. Sneen, *Accounts Chem. Res.*, **6**, 46 (1973).

(11) J. D. Dunitz, "Perspectives in Structural Chemistry," Vol. 2, J. D. Dunitz and J. A. Ibers, Ed., Wiley, New York, N. Y., 1968, p 1.

(12) H. M. R. Hoffmann and J. G. Vinter, submitted for publication.

Table VI. Product Ratios[a] from the Reaction of α,α'-Dibromocycloalkanones with Zinc–Copper Couple in the Presence of Furan

α,α'-Dibromo-cycloalkanone n	Parent cycloalkanone[b]	2-(2'-Furanyl)-cycloalkanone	$C_{aa}n$	$B_{aa}n$ and/or $C_{ee}n$	$C_{ae}n$	Compact vs. extended cycloaddition
7 trans	53 (61%)	Trace	36	1	1	36:1 ($C_{aa}7:B_{aa}7$)
8 trans	30 (83%)	Trace	5	1		5:1 ($C_{aa}8:B_{aa}8$)
10 trans	13 (68%)	1			5[c]	6:1[c]
10 cis	30 (83%)	1			5[c]	6:1[c]
11 dl	15 (64%)	0.5	1	6	1	6:1 ($B_{aa}11:C_{aa}11$)
11 meso	4 (32%)	0.5	1	6	1	6:1 ($B_{aa}11:C_{aa}11$)
12 meso	3 (26%)	0.5	1	6	1	6:1 ($C_{ee}12 \rightleftharpoons B_{aa}12)/C_{aa}12$
13 mp 110°	5 (36%)	0	1	6	2	6:1 ($C_{ee}13 \rightleftharpoons B_{aa}13)/C_{aa}13$

[a] Determined by glc after hydrogenation of reaction mixture; retention times were in the order cycloalkanone, 2-(2'-furanyl)cycloalkanone, hydrogenated tricyclic adducts. The dimeric cycloalkanone (0–10% overall yield) is not listed, since it tended to be retained by the column. For this reason no absolute yields are given in the table. [b] Approximate overall yield given in parentheses. [c] Reaction mixture contains traces of other products including possibly $B_{ae}10$ ($C_{ae}10:B_{ae}10 \sim 6:1$).

with 2,7-dibromocycloheptanone. In this instance the intermediate U cation is forced to adopt a nearly planar conformation and the compact combination leading to $C_{aa}7$ seems to be favored sterically in that it avoids a clash between furan and the methylene chain. Perhaps the argument may be restated somewhat more convincingly by saying that on conformational grounds $C_{aa}7$ is strongly favored over $B_{aa}7$ which is a rather strained boat (cf. its nmr spectrum and carbonyl stretch frequency in Table IV).

The reaction of trans-2,10-dibromocyclodecanone [bp 60–64° (0.001 mm)] and furan was very clean and gave two cycloadducts, the major one being $C_{ae}10$, which also arose from cis-2,10-dibromocyclodecanone (mp 55°). The higher yield of $C_{ae}10$ from trans- vis-à-vis cis-2,10-dibromocyclodecanone was reproduced several times and is therefore felt to be significant. We suggest that the trans epimer, which has a much lower carbonyl stretch frequency than the cis isomer,[12] is more prone toward quasiaxial departure of bromine and, hence, can form an allyl cation more readily. The minor cycloadduct was not isolated in pure form but, on the basis of its pmr spectrum and glc retention time after reduction, was most likely $B_{ae}10$. Ordinarily, one would not expect to be able to distinguish compact and extended transition states when using sickle allyl cations. The ten-membered sickle cation might well be unique in that it not only arises relatively cleanly but also affords two conformationally rigid adducts, i.e., $C_{ae}10$ and $B_{ae}10$. In fact, one can argue that in forming a sickle cation, the Dunitz conformation of the ten-membered ring[11] is maintained as far as possible, while larger rings approach open-chain behavior.
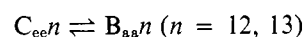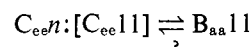
In any case, the compact/extended ratio is roughly constant for $n = 8$, 11–13, possibly for $n = 10$ and for the acyclic 1,3-dimethyl-2-oxyallyl cation generated with zinc–copper couple.[2a] Within that series of allyl cations, the geometry changes from U to W and sickle form, yet judged by the common compact/extended ratios, the transition states leading to the various cycloadducts must be similar in that steric or conformational differences—which are evident in the final products—have not yet made much impact. Seen in this light our work provides a striking demonstration of a reactant-like, 6π 7 C aromatic transition state in an intermolecular cycloaddition.[13]

(13) (a) Independently, aspects of our work[6] have been studied by two Japanese groups; see ref 13b and ref 18 below. We agree that $C_{aa}7$ is the major product of the debromination of 2,7-dibromocycloheptanone in the presence of furan. Presumably, the oily and rather

Finally, we briefly summarize our views on the mode of formation of the various tricyclics.

$C_{aa}n:C_{aa}7$ and $C_{aa}8$ arise via U cations and compact transition states. $C_{aa}11$, $C_{aa}12$, and $C_{aa}13$ are secondary products from $[B_{ee}n]$ ($n = 11$–13). The latter class of tricyclics is formed from W cations via extended transition states.

$B_{aa}n:B_{aa}7$ and $B_{aa}8$ arise via U cations and extended transition states. $B_{aa}11$, $B_{aa}12$, and $B_{aa}13$ are secondary products formed from $[C_{ee}11]$, $C_{ee}12$, and $C_{ee}13$ (which arise via W cations and compact transition states). $C_{ae}n$ is formed when $n = 10$–12 but not for $n = 7$ or 8. These are primary and/or epimerization products and could also arise in minor amounts from $B_{ae}n$. $B_{ae}n$: $B_{ae}10$ is a possible, conformationally frozen derivative.

$$B_{ee}n:[B_{ee}n] \rightleftharpoons C_{aa}n \ (n = 11\text{–}13)$$

$$C_{ee}n:[C_{ee}11] \underset{?}{\rightleftharpoons} B_{aa}11$$

$$C_{ee}n \rightleftharpoons B_{aa}n \ (n = 12, 13)$$

Experimental Section

Instrumentation. Routine pmr spectra were recorded on a Perkin-Elmer R10 60-MHz instrument, while the more precise work including decoupling experiments was performed on a Varian HA-100, 100-MHz variable temperature spectrometer. Ir spectra were obtained on a Perkin-Elmer 257 grating spectrometer and an AEI MS12 instrument was used for recording routine mass spectra. The apparatus for measuring dipole moments was built in the laboratory as a temporary set-up, using a Muirhead Type A-411-B variable air condenser (range 1250 pF) incorporated into an RC bridge. The cell consisted of four stainless steel electrodes fitted into a glass vessel of about 40-ml capacity. All the dipole moments were measured in dry benzene solution.

Cycloaddition Procedure. Introduction. 2,4-Methylated 8-oxa-bicyclo[3.2.1]oct-6-en-3-ones were prepared previously by adding the α,α'-dibromo ketone in solvent glyme to a suspension of zinc–copper couple in furan.[2a] Several problems arose from the use of medium and large dibromocycloalkanones[12] as starting materials.

(i) The higher dibromo ketones were not sufficiently soluble in these conditions. Benzene was therefore used as the principal solvent.[14]

polar $B_{aa}7$ escaped detection in both studies, since in any case its proportion is very low ($C_{aa}7*B_{aa}7 = 36:1$ in our conditions; see Table VI). The greater propensity of cyclopentadiene vis-à-vis furan toward the extended transition state[2a,c] seems to be borne out by Itô's work[18] with 2,7-dibromocycloheptanone. From our experience a tricyclic adduct of mp 58–60°, which has been considered to be $C_{ae}12$ by Noyori, et al.,[13b] is a mixture of mainly the mobile pair $C_{ee}12 \rightleftharpoons B_{aa}12$ and $C_{ae}12$. The compounds can be separated by crystal picking as described in the Experimental Section. (b) R. Noyori, Y. Baba, S. Makino, and H. Takaya, Tetrahedron Lett., 1741 (1973).

(14) See also H. M. R. Hoffmann and D. R. Joy, J. Chem. Soc. B, 1182 (1968); A. E. Hill and H. M. R. Hoffmann, J. Amer. Chem. Soc., 96, 4597 (1974).

(ii) As a consequence of the solvent change to benzene, debromination no longer occurred in one-flask conditions. This problem was overcome by the continuous flow technique.

(iii) In order to improve the flow rate through the column, alumina was used as a diluent (alumina for chromatography, Brockmann grade II-III). The basic properties of alumina could also help in trapping stray acid and cleaning the reaction solution of any acidic or polar impurities. Furthermore, the reactive surface of the metal is increased, while "holes" are created to accommodate reagents and products.

(iv) Formation of α-acetoxy- and α-hydroxycycloalkanones as by-products in the earlier reactions suggested the interference of acetate ions and water which were found to be residual in the Le-Goff zinc–copper couple[15] and could not be removed without destroying the activity of the metal. A new couple was prepared.

Preparation of a Dry, Acid-Free Zinc–Copper Couple on Alumina. Cupric chloride dihydrate (20 g) was kept at 150–200° for at least 3 hr and then stirred rapidly into acetone (500 ml, AnalaR) at 50°. Alumina (40 g, Brockmann grade II-III) was mixed with zinc dust (220 g) and added to the acetone mixture with rapid swirling over a period of 3 min, heat being generated in the process. The resulting zinc–copper couple was collected on a large glass sinter funnel, washed with acetone (ca. 200 ml, AnalaR) and dry ether (ca. 300 ml), and finally air-dried at 50° or dried *in vacuo*.

Column Technique. In the standard set-up a column equipped with a cooling device was connected at the top to a reservoir containing the solution of the reagents and at the bottom to a flask which had a nitrogen outlet and a pressure-compensating tube leading to the top. The bottom of the column was plugged with cotton wool and then packed with alumina followed by zinc–copper couple on alumina. In order to avoid clogging which tended to occur in the upper region of the column, a metal–alumina gradient was erected with maximum dilution with alumina near the top. In this way a reasonable flow rate (10–50 ml/hr) through the column was attained.

The reaction itself was started by flushing a small quantity of dried benzene (ca. 20 ml) down the column as a solvent front and then introducing the reaction mixture made up from dibromo ketone (0.06 M) dissolved in sodium dried benzene (150 ml) containing glyme (10 ml) and furan (20 ml). (The commercial grade of glyme as well as furan must be redistilled from calcium hydride to remove water and peroxides.)

The reaction usually took place over the first few centimeters of the column length as indicated by the color change of the metal from grey to copper red. The average time taken for the reaction mixture to pass once down the column was 2–6 hr depending on the column packing and the grade of the couple. If the flow rate was too fast no reaction ensued, while a very slow rate was inconvenient. If any dibromo ketone had remained after the first pass, it was detected by nmr and further passes were performed until debromination was complete. The column was finally washed through with dried benzene (ca. 100 ml).[15a]

On addition of water to the combined eluate, the precipitation of white, insoluble zinc complexes was usually observed. These salts were removed by filtration through cellulose powder, and after two more washings with water (ca. 600 ml altogether) the organic layer was dried (CaCl₂) and the solvent removed at reduced pressure yielding in the instance of the 2,12-dibromocyclododecanone reaction a greenish oil, the separation of which is described below. Typical recovery statistics for this particular reaction were as follows: input, *meso*-2,12-dibromocyclododecanone (20 g); output, oily product (14 g) + zinc–glyme complexes. From separation of the oily product: (1) solid (cycloadduct + dimer), 6.4 g; (2) oil (parent ketone 40%, cycloadduct 50%, by-products 10%), 4.3 g.

For all other α,α'-dibromocycloalkanones the total recovery was similar, but the percentage conversion into tricyclic adducts varied and was lowest for medium rings (Table VI).

Comments on the New Dehalogenation Technique. For several reasons the continuous flow procedure serves as a useful adjunct to the batchwise method described previously.[2a] First of all, dehalogenation of the dibromo ketone can be forced to completion under mild conditions even when using solvents of low polarity, e.g., benzene as in the present work or pentane.[16] Further, work-up of the products is easy in that it is unnecessary to filter the metal

residue from the reaction mixture. In fact, the reaction solution obtained is quite clean, and any polymeric by-products stay behind on the top of the column. Finally, the column itself can be used several times until the couple is exhausted, as indicated by the color of the metal.

Separation and Identification of the Tricyclic Adducts (See Also Tables III-VII). **11-Oxatricyclo[6.2.1.1²·⁷]dodec-9-en-12-one ($C_{aa}7$ and $B_{aa}7$).** After work-up of the crude benzene reaction mixture with water, an oil was obtained which was submitted to dry column chromatography[17] on aluminium oxide (Brockmann grade II-III) and eluted with pentane to separate cycloheptanone. Further elution with pentane-ether (10:1 v/v) afforded $C_{aa}7$: mp 50°. after recrystallization from isopentane at −78°; dipole moment 1.9 D; nmr (TMS, CCl₄) 6.22 (2 H, s), 4.60 (2 H, s), 2.39 (2 H, complex), 2.2-1.1 (8 H). (The reported vicinal coupling $J_{ml} = 1.3$ Hz[18] was not detected, $J_{mb} < 0.4$ Hz in our conditions; see also Table I.) Final elution with pentane-ether (1:1 v/v) separated a minor amount of a more polar, greenish oil which after treatment with animal charcoal in ether gave $B_{aa}7$ as an almost colorless, viscous liquid that did not crystallize on cooling: nmr (TMS, CCl₄) 6.50 (2 H, s), 4.84 (2 H, d, $J_{mb} = 8.5$ Hz), 3.16 (2 H, m), 2.7-1.0 (8 H).

12-Oxatricyclo[7.2.1.1²·⁸]tridec-10-en-13-one ($C_{aa}8$ and $B_{aa}8$). Treatment of 2,8-dibromocyclooctanone as above gave the high melting cycloadduct $C_{aa}8$: mp 52°; nmr 6.22 (2 H s), 4.60 (2 H, s), 2.1 (2 H, br t), 2.0-1.0 (10 H). A more polar oil, which had longer retention times on dry column and gas chromatography, was identified as $B_{aa}8$: nmr 6.47 (2 H, s), 4.76 (2 H, d, $J_{mb} = 8.0$ Hz), 3.0-1.0 (12 H); the protons α to the CO group appear as a broad peak at 2.7-3 ppm.

14-Oxatricyclo[9.2.1.1²·¹⁰]pentadec-12-en-15-one ($C_{ae}10$). *cis-* as well as *trans*-2,10-dibromocyclodecanone were debrominated with zinc–copper couple in the presence of furan to give a crude oily product which was cooled to −78° in isopentane. The resulting solid was washed in the cold with a little more isopentane to yield microcrystals of $C_{ae}10$: nmr 6.08 [2 H, AB type quartet ($J_{mb} = 5.9$ Hz); each line split further into a doublet ($J_{vic} \sim 1.7$ Hz) due to coupling with the bridgehead protons; the two pairs of outer lines are hard to see], 4.60 (2 H, complex), 3.92 (1 H, d, complex), 2.28 (1 H, br), 2.0-1.0 (14 H).

A minor product which was formed in a ratio of ca. 1:6 with respect to $C_{ae}10$ [and was not 2-(2'-furanyl)cyclodecanone] was tentatively identified as $B_{ae}10$ without complete separation. It showed an olefinic AB quartet diagnostic of axial, equatorial tricyclics at 6.2 ppm and further peaks in the bridgehead and α-methine region.

15-Oxatricyclo[10.2.1.1²·¹¹]hexadec-13-en-15-one ($C_{aa}11$, $C_{ae}11$, and $B_{aa}11$). The reaction products from debromination of 2,11-dibromocycloundecanone were worked up by treatment with water. After removal of benzene the remaining oil was dissolved in isopentane and stored at 0° for a few days before chromatography. In this way, solid cycloaddition products and any cycloundecanone dimer were separated from cycloundecanone which is readily soluble in isopentane. The remaining solid was treated with pentane (industrial grade) to remove cycloundecanone dimer, which once it had crystallized was even insoluble in acetone. The pentane-soluble cycloadducts were then chromatographed on an alumina dry column to yield on elution with pentane the symmetric adduct $C_{aa}11$ [mp 130; large plates; nmr 6.14 (2 H, s), 4.54 (2 H, s), 2.12 (2 H, br), 1.9-1.0 (16 H)] and also microcrystals of the unsymmetric adduct $C_{ae}11$ [mp 65°; nmr 6.09 (2 H, AB type quartet, each line split further into a doublet; the two pairs of outer lines are hard to see), 4.60 (2 H, complex), 3.41 (1 H, complex doublet which is more narrow than the corresponding one of $C_{ae}10$), 2.22 (1 H, br and complex), 1.31 (16 H, br)].

The third, most polar and major cycloadduct, $B_{aa}11$, was obtained by elution with ether, fractional crystallization from isopentane, and separation of the resulting needles: nmr 6.38 (2 H, s), 4.82 (2 H, d, $J_{mb} = 7.5$ Hz), 2.78 (2 H, br), 1.9-1.0 (16 H); dipole moment 2.9 D.

16-Oxatricyclo[11.2.1.1²·¹²]heptadec-14-en-17-one ($C_{aa}12$, $C_{ae}12$, $C_{ee}12$, and $B_{aa}12$). 2,12-Dibromocyclododecanone was debrominated with zinc–copper couple as described in the introduction to produce a mixture of cycloadducts which was dissolved in isopentane and stored at 0° for 2 days. The resulting solid was slowly and carefully recrystallized (ca. 2 days at 25°) from isooctane to yield two distinct forms of crystals which were separated manually.

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

(15a) NOTE ADDED IN PROOF. The column procedure has been used recently by J. F. Ruppert and J. D. White, *J. Org. Chem.*, 39, 269 (1974), in a study of the Reformatsky reaction.

(16) R. Chidgey, unpublished results.

(17) B. Loev and M. M. Goodman, *Chem. Ind. (London)*, 2026 (1967).

(18) S. Itô, H. Ohtani, and S. Amiya, *Tetrahedron Lett.*, 1737 (1973).

Table VII. Selected Analytical Data of the Tricyclic Adducts

Tricyclic adduct	Mp, °C	Appearance	Chromatographic eluent	Crystn medium	Calcd C	Calcd H	Found C	Found H
$C_{aa}7$	50[a]	Colorless micaceous	Pentane–ether (10:1 v/v)	Isopentane	74.13	7.92	74.04	7.94
$C_{aa}8$	52[b]	Microcrystals	Pentane	Isopentane	74.97	8.39	74.33	8.34
$C_{aa}11$	130	Plates	Pentane	Isopentane	76.92	9.40	76.41	9.32
$C_{aa}12$	130–158[c]	Plates or needles	Ether	Isooctane Hand picked	77.34	9.74	77.60	9.78
$B_{aa}7$	Oil	Pale green	Ether					
$B_{aa}8$	Oil	Yellow	Ether					
$B_{aa}11$		Needles	Ether	Isopentane				
$C_{ee}12 \rightleftharpoons B_{aa}12$[d]	85	Rhomboids	Ether	Isooctane Hand picked	77.34	9.74	77.33	9.63
$C_{ee}13 \rightleftharpoons B_{aa}13$	100	Needles	Ether	Isopentane	77.90	9.99	77.99	10.03
$C_{ae}10$		Microcrystals	Ether					
$C_{ae}11$	65	Microcrystals	Pentane	Isopentane	76.92	9.40	77.04	9.40

[a] Mp 49–50° (ref 18) and 51° (ref 13b). [b] Mp 50–52°: ref 13b. [c] Dependent on speed of heating; mp ~150° in ref 13b; mass spectrum M^+ 248. [d] See footnote 13; mass spectrum M^+ 248.

The highest melting and minor isomer (mp 130–158° depending on the speed of heating) was $C_{aa}12$: nmr 6.16 (2 H, s), 4.62 (2 H, s), 2.16 (2 H, br), 2.0–1.4 (18 H); dipole moment 1.7 D. The major isomer, mp 85°, showed twin ir carbonyl absorptions at 1714 and 1704 cm^{-1} in CCl$_4$ and a single carbonyl band at 1713 cm^{-1} in the mull (Figure 6). The dipole moment was 2.4 D. While the nmr spectrum was unresolved at room temperature, on cooling to 0° two individual conformers were clearly discernible. Nmr (TMS, CCl$_4$) of $C_{ee}12$: 6.15 (2 H, s), 4.76 (2 H, d, J = 3.5 Hz), 3.32 (2 H, complex), 1.3 (18 H, br). Nmr of $B_{aa}12$: 6.42 (2 H, s), 4.88 (2 H, d, J = 7.5 Hz), 2.78 (2 H, complex), 1.3 (18 H, br). At 60° the olefinic resonances of $C_{ee}12 \rightleftharpoons B_{aa}12$ coalesced to a sharp signal at 6.20 ppm, and the bridgehead resonances appeared as a doublet at 4.68 ppm (J_{mb} = 5.5 Hz). In acetone solution at 60° J_{mb} increased to 6.0 Hz (see also Table X and Figure 7).

Further separation of the isooctane mother liquor by dry column chromatography yielded cyclododecanone and the unsymmetric adduct $C_{ae}12$: nmr 6.12 (2 H, AB type quartet, each line split into doublet due to coupling with bridgehead protons), 4.58 (2 H, complex), 3.28 (1 H, complex d), 2.10 (1 H, complex), 1.8–1.0 (18 H); ir (CCl$_4$) ν_{CO} 1713 cm^{-1}.

17-Oxatricyclo[12.2.1.1^{2,13}]octadec-15-en-18-one ($C_{ee}13 \rightleftharpoons B_{aa}13$). Debromination of 2,13-dibromocyclotridecanone of mp 110° in the presence of furan gave a mixture of cycloadducts which was stored at 0° in isopentane to remove cyclotridecanone and any dimeric cyclotridecanone after it had crystallized. Dry column chromatography of the isopentane mother liquor and elution with ether afforded a tricyclic adduct which after recrystallization from isopentane formed colorless needles: mp 100°; dipole moment 2.3 D; ir (CCl$_4$)ν_{CO} 1714 cm^{-1} br, weak shoulder at ca. 1703 cm^{-1}; nmr of $C_{ee}13 \rightleftharpoons B_{aa}13$ (TMS, CDCl$_3$) 6.20 (2 H, s), 4.76 (2 H, d, J = 5.5 Hz), 2.96 (2 H, complex), 1.9–1.1 (20 H) (Figure 7). The spectrum was very similar to that of $C_{ee}12 \rightleftharpoons B_{aa}12$ at 100°, but unlike the earlier one could not be resolved on cooling; at the lower temperature limit of −80° the tricyclic was no longer sufficiently soluble in CFCl$_3$ and CDCl$_3$ for recording a spectrum.

Identification of Products Other than Tricyclic Adducts. (1) Parent Cycloalkanone. Generally, parent cycloalkanone was formed in all debrominations, especially from medium ring precursors (Table VII). It was detected easily as a volatile compound by glc; on column chromatography the parent cycloalkanone was also eluted first (pentane solvent).

(2) Dimeric Cycloalkanone. The glc retention times of di(cyclo-alkanon-2-yl) compounds (meso and dl) were very long and the nmr resonances could not be clearly distinguished from those of other compounds such as parent cycloalkanone and polymeric cyclo-alkanone. However, once the dimer had crystallized it appeared to be insoluble in nonpolar solvents and in this way could be separated. Of the total debrominated products di(cycloalkanon-2-yl) constituted 0–10% and it appeared to be formed preferentially in the presence of weak proton donors. A more detailed study of these 1,4-diketones has been reported elsewhere.[19]

Other Reactions. Additives and Variations in Technique. For

the following experiments the general cycloaddition procedure was scaled down by a factor of 10.

(1) Addition of 2,6-Lutidine. meso-2,12-Dibromocyclodode-canone was debrominated in the presence of furan after 2,6-lutidine had been added in varying amounts. After aqueous work-up the product ratios were determined by nmr. In general, the cyclo-addition was found to be inhibited, 2-bromocyclododecanone being a major product (Table VIII).

Table VIII. Products of the Debromination of meso-2,12-Dibromocyclododecanone in the Presence of Furan and 2,6-Lutidine

Reagents α,α'-Dibromo ketone:2,6-lutidine	Products α-Bromo ketone:α,α'-dibromo ketone	Cycloadducts
6:1	1:3	
10:1	1:3	
20:1	1:3	
40:1	1:5	
60:1	1:3	Trace
500:1	Traces	Yes

(2) Addition of Acetic Acid. The addition of acetic acid (ratio of meso-2,12-dibromocyclododecanone:acetic acid = 1.75:1, 3:1, 4.5:1, 15:1) had no marked effect on the distribution of products, judging by control experiments.

Thus, within the limits of nmr detectability no additional cyclo-dodecanone was formed and an increase in the yield of cycloadducts was not observed. Furthermore, no additional 2-acetoxycyclo-dodecanone appeared to be formed when using the LeGoff zinc-copper couple.[15] Presumably, indigenous acetic acid on the Le-Goff couple is responsible for the formation of 2-acetoxycyclodode-canone.

(3) Debromination in Benzene Solvent in the Absence of Glyme. 2,12-Dibromocyclododecanone and trans-2,10-dibromocyclodeca-none were not debrominated under the usual conditions in the absence of glyme. However, after meso-2,12-dibromocyclo-dodecanone (5 g) had been left on the column without elution for over 3 days in the presence of furan (5 ml) and benzene (100 ml), work-up and nmr analysis revealed the formation of high melting $C_{aa}12$, some parent cyclododecanone, and a major amount of 2-(2'-furanyl)cyclododecanone: mp 57°; nmr (TMS, CCl$_4$) 8.3 (1 H, complex), 7.3 (1 H, complex quartet), 7.1 (1 H, complex), 4.8 (1 H, complex quartet), 1.4–3.0 (20 H, br); mass spectrum m/e 248, 220, 81, and loss of 84 from 191 to 107. Anal. Calcd for $C_{16}H_{24}O_2$: C, 77.34; H, 9.74. Found: C, 77.22; H, 9.77.

The worked up eluate was deep red. Separation of the colored material afforded a viscous oil which showed no olefinic protons but only a broad band at δ 1.3 ppm in the nmr, conceivably due to a polymeric cyclododecanone derivative [cf. also the formation of di-(cyclododecanon-2-yl)].

(4) Debromination without Aqueous Work-Up in the Absence of Furan. Debromination in benzene and glyme followed by removal

(19) C. Chassin, E. A. Schmidt, and H. M. R. Hoffmann, J. Amer. Chem. Soc., 96, 606 (1974).

of the bulk of benzene at reduced pressure gave two broad nmr peaks at δ 3.65 and 3.45 ppm in variable intensities [glyme peaks are sharp at δ 3.45 (2 H) and 3.30 (3 H)]. After prolonged evaporation at reduced pressure only the singlet at δ 3.45 remained. If the reaction mixture was not concentrated, a further sharp singlet at δ 7.5 was observed. Presumably, these peaks are due to secondary products from glyme.

A sample of the reaction mixture was concentrated on a rotary film evaporator to a cloudy oil, which on addition of CCl$_4$ precipitated di(cyclododecanon-2-yl) (meso and *dl*) as a white solid. The residual oil contained parent cyclododecanone and a colored viscous oil with nmr resonances only in the δ 1.3-ppm region (polymeric cyclododecanone?).

(5) **Variations in Couple.** Initially, the zinc-copper couple was prepared according to LeGoff[16] by addition of metallic zinc to a solution of hydrated cupric acetate in glacial acetic acid. The resulting couple smelled strongly of acetic acid which could not be removed even by prolonged washing with ether or at high vacuum for 2 days. Debromination with the new acetate and water-free couple described above stopped the formation of the undesired 2-hydroxycycloalkanones and 2-acetoxycycloalkanones, whereas the ratio of cycloadducts to parent cyclcalkanones remained constant.

A zinc-nickel couple prepared from anhydrous nickel chloride gave products similar to those from the acid-free zinc-copper couple.

Detailed Study of the Conformationally Mobile Tricyclics. The equilibrium $C_{ee}12 \rightleftharpoons B_{aa}12$ was investigated quantitatively in solvent $(CD_3)_2CO$ and in CCl$_4$ by a complete line-shape analysis.[20] Spectra were recorded at 5° temperature intervals under slow sweep conditions, and the line shapes were compared with those from calculated spectra using various rate constants. In the present instance the analysis was simplified by the fact that only negligible couplings existed between the olefinic protons and their neighbors and that nearly equal populations of $C_{ee}12$ and $B_{aa}12$ were encountered. The activation entropy $\Delta S^{\ddagger}$ and activation enthalpy $\Delta H^{\ddagger}$ were determined in the usual way from the free energy of activation $\Delta G^{\ddagger}$; ΔG refers to the relative population of the ground states[21] (Tables IX and X).

$C_{ee}13 \rightleftharpoons B_{aa}13$. In this case no change in the nmr spectrum was observed on cooling a CFCl$_3$ solution down to $-80°$. Assuming

Table IX. Activation Parameters for the Equilibrium $C_{ee}12 \rightleftharpoons B_{aa}12$

	ΔG, kcal/ mol	Pre-dominant conformer	$\Delta G^{\ddagger}$, kcal/ mol	$\Delta H^{\ddagger}$, kcal/ mol	$\Delta S^{\ddagger}$, eu	Solvent
	0.04	$C_{ee}12$, 66%	16.0	16.7	1.5	CCl$_4$
	-0.6	$B_{aa}12$, 73%	15.8	16.3	1.5	$(CD_3)_2CO^a$
Error	$\pm 25\%$		$\pm 1.7\%$	$\pm 3\%$	$\pm 50\%$	

^{a} Note that the activation parameters given in ref 6 refer to the reverse process, *i.e.*, the conversion of boat into chair.

Table X. Solvent Effects on the Equilibrium $C_{ee}12 \rightleftharpoons B_{aa}12$ at 35°

	—Approx populations^a—		Solvent dielectric constant^b
Solvent	$B_{aa}12$	$C_{ee}12$	
Cl$_2$CCCl$_2$	0.6	1	
CFCl$_3$	0.9	1	
CCl$_4$	1.1 $\pm$ 0.2	1	2.2
C$_6$H$_6$	1.3	1	2.3
CH$_2$Cl$_2$	1.3	1	8.9
Me$_2$SO	1.3	1	48.9
CDCl$_3$	1.7	1	4.7
MeCN	1.8	1	37.5
Me$_2$CO	2.4	1	20.7
MeOH	2.6	1	32.6

^{a} Determined from peak heights of 60-MHz nmr spectra. ^{b} F. W. Fowler, A. R. Katritzky, and R. J. D. Rutherford, *J. Chem. Soc. B*, 460 (1971); see also C. Reichardt, *Angew. Chem., Int. Ed. Engl.*, **4**, 29 (1965).

(20) We thank Dr. J. E. Anderson for the computer program.
(21) G. Binsch, *Top. Stereochem.*, **3**, 97 (1968); I. O. Sutherland, *Annu. Rep. NMR Spectrosc.*, **4**, 71 (1971).

Table XI. Chemical Shifts, δ (TMS, CCl$_4$), of Hydrogenated Tricyclic Adducts^a

Hydrogenated tricyclic	Bridgehead protons	Equatorial protons	Axial protons
$C_{aa}7(2H)$	4.31	~ 2.37	
$C_{aa}8(2H)$	4.23	~ 2.37	
$C_{aa}11(2H)$	4.22	2.04	
$C_{aa}12(2H)^b$	4.27	2.04	
$B_{aa}11(2H)$	4.44	2.64	
$C_{ae}11(2H)$	4.35	2.20	3.30
$C_{ee}11(2H)$	4.36		3.04
$C_{ee}12(2H)^c$	4.36		3.16
$C_{ee}13(2H)$	4.30		2.90

^{a} For broad and multiple peaks mean chemical shifts are given; solutions *ca.* 0.05-0.1 *M*. ^{b} Mp 100°; mass spectrum *m/e* 250. ^{c} Mp 95°. *Anal.* Calcd for $C_{16}H_{26}O_2$: C, 76.76; H, 10.47. Found: C, 76.03; H, 10.29.

a chemical shift differenc of 0.27 ppm for the olefinic protons (as for $C_{ee}12 \rightleftharpoons B_{aa}12$), $\Delta G^{\ddagger} < 9$ kcal/mol for the interconversion of $C_{ee}13 \rightleftharpoons B_{aa}13$ at $-80°$. An estimate of the pcpulation of $C_{ee}13$ and $B_{aa}13$ was obtained from the observed value of J_{mb} as follows. For $C_{ee}12$, $J_{mb} = 3.5$ Hz; simple bicyclic model compounds[2a,4] show $J_{mb} = 5$ Hz (Figure 4). For $B_{aa}11$ and $B_{aa}12$, $J_{mb} = 7.5$ Hz.

Now $C_{ee}13 \rightleftharpoons B_{aa}13$ at rapid equilibration shcws $J_{mb} = 5.0$ Hz in $(CD_3)_2CO$ and CDCl$_3$ solvent; $J_{mb} = 4.5$ Hz in CCl$_4$. Conformaticnally pure $C_{ee}13$ must therefore have 3.5 Hz $\leq J_{mb} \leq 4.5$ Hz. As chemical shifts coalesce, the coupling constants average to the weighted mean of the two individual conformers. Let J_{mb}-$(C_{ee}13) = 3.5$ Hz [solvents $(CD_3)_2CO$, CDCl$_3$]; $5.0 = 3.5(1 - x) + 7.5 x$, where x is the fraction of $B_{aa}13$. Hence, the population of $B_{aa}13 = 38\%$ in $(CD_3)_2CO$ and CDCl$_3$, but 25% in CCl$_4$. Let $J_{mb}(C_{ee}13) = 4.5$ Hz. Now the population of $B_{aa}13 = 17\%$ in $(CD_3)_2CO$ and CDCl$_3$, but *ca.* 0% in CCl$_4$.

In summary, the pcpulation of $C_{ee}13$ amounts to $87 \pm 13\%$ in CCl$_4$ at 25°, but only $73 \pm 10\%$ in the more polar solvents $(CD_3)_2CO$ and CDCl$_3$.

$B_{aa}11 \rightleftharpoons C_{ee}11$? No changes in either the coupling constant or the appearance of the downfield olefinic resonance were observed in the nmr spectrum up to 140° in hexachlorobutadiene and diglyme solution. Hence, either the barrier $\Delta G^{\ddagger}$ to interconversion is higher than 22 kcal/mol or the chair is thermodynamically much less stable than the boat.

$B_{aa}11(2H) \rightarrow C_{ee}11(2H)$. The transformation of boat atropisomer into chair was determined by measuring the rate of growth of the methine protons of $C_{ee}11(2H)$ at 74°; $\Delta G^{\ddagger} = 25.7 \pm 0.5$ kcal/mol. In an independent and earlier investigation the rate of disappearance of the methine protons of $B_{aa}11(2H)$ was monitored: $\Delta G^{\ddagger} = 25.8 \pm 1$ kcal/mol. The pmr spectrum of $C_{ee}11(2H)$ up to 160° showed no evidence for any reversion into $B_{aa}11(2H)$

Cleavage of the Tricyclics to 2-(2'-Furanyl)cycloalkanones. The conformationally mobile tricyclics and $C_{ae}n$ derivatives decomposed on heating and on treatment with anhydrous HCl in ether or methanolic ZnBr$_2$ to give 2-(2'-furanyl)cycloalkanones. For example, mixed crystals of $C_{aa}12$ and $C_{ee}12 \rightleftharpoons B_{aa}12$ were left at 70° for 100 hr and examined by nmr in timed intervals. While $C_{aa}12$ remained unchanged, the peaks due to $C_{ee}12 \rightleftharpoons B_{aa}12$ disappeared and 2-(2'-furanyl)cyclododecanone, mp 57° after chromatography on ZnCl$_2$ impregnated silica gel and recrystallization from isopentane, was formed. The same compound was obtained by (i) heating pure $C_{ee}12 \rightleftharpoons B_{aa}12$ to 70° for 24 hr, (ii) dissolving $C_{ee}12 \rightleftharpoons B_{aa}12$ in ether, which was saturated with gaseous HCl at 25°, and work-up after 12 hr, and (iii) dissolving $C_{ee}12 \rightleftharpoons B_{aa}12$ in a methanolic solution of anhydrous ZnBr$_2$ (from ZnSO$_4$ + 2NaBr) and work-up after 10 hr at 25°. $C_{aa}12$ was not affected after being heated to 70° for 2 days or by hydrogen chloride at 25°.

$B_{aa}11$ was only partly cleaved in ethereal HCl after 24 hr; on heating to 150° the conversion into 2-(2'-furanyl)cycloundecanone was complete within 10 min.

2-(2'-Furanyl)cycloalkanones were usually detected to a small extent in the reaction mixtures after cycloaddition except in the case of the 13-membered ring. However, after heating a sample of $C_{ee}13 \rightleftharpoons B_{aa}13$ to 100° for 6 hr, 2-(2'-furanyl)cyclotridecanone was identified.

Hydrogenation of the Tricyclics. As an independent check of the number of products formed during cycloaddition, the various reac-

tion products were worked up as before, then hydrogenated (ethyl acetate, Adams catalyst), and analyzed by glc (100-ft Carbowax 20M column, 200° for derivatives of $n = 7, 8, 10$ and 220° for $n = 11$–13). Major peaks were identified by comparison with authentic samples where these were available and by integrating the corresponding nmr spectra. The data in Table VI were reproducible to the extent that the average ratio of compact vs. extended attack was about (6 ± 1):1. The sensitivity of the detector to 2-(-(2′-furanyl)cycloalkanones was felt to be low and consequently the amounts of this product could have been underestimated.

The ir and nmr data of the hydrogenated tricyclics are collected in Table I and Table XI, respectively.

Mechanistic and Synthetic Applications of Silver(I)-Promoted Alkoxyl Group Ionization Processes. An Evaluation of Cyclopropylcarbinyl and Benzhydryl Ethers[1,2]

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Abstract: The reaction of a number of endo-2-methoxytricyclo[4.1.0.0³·⁷]heptanes with silver perchlorate in benzene at 40° leads to quantitative isomerization to anti-7-methoxynorbornenes by a process involving initial $Ag^+ \cdots OR(CH_3)$ coordination, methoxyl group ionization, and recapture of the alkoxide after cyclopropylcarbinyl → homoallyl rearrangement. Several norcaranyl ethers were examined under comparable conditions; depending upon structure, rearrangement, simple "demethanolation," or loss of methanol with ring opening was observed. Autocatalytic acid production was noted in one system but not another. The reactivity of dicyclopropylcarbinyl methyl ether was also assessed. The reaction of benzhydryl ethers with silver salts in aqueous methanol serves as a convenient and mild method for liberating a hydroxyl group in the presence of other sensitive functions. The potential applications of these transformations are discussed.

O ver the years, innumerable investigations of solvolysis reactions have provided much detailed information about the structure and behavior of carbonium ions, as well as the fundamental role played by solvents in the generation and destruction of such ions.[4] Generalized reaction schemes involving a spectrum of intermediates ranging from free carbocations to intimate ion pairs have been developed to accommodate the reactivity of these charged sp^2-hybridized systems.[4,5] It was apparent when we initiated the present investigation that much of the previous work had been conducted in solvents endowed either with appreciable nucleophilicity, high dielectric constant, protic characteristics, or a combination of these features.

An alternative powerful way to study carbonium ions is to promote their formation under conditions of essentially neutral pH in solvents of negligible nucleophilicity. Complications due to proton sensitivity,

solvation, and various related factors would thereby be minimized. More specifically, solvent perturbation of the ionization process per se would be greatly reduced and the absence of a solvation shell could also affect the movement of atoms more remote from the reaction site. Such would represent a deep-seated modification of the usual environment of bond heterolysis processes and could in principle provide important information about carbocation-forming reactions.

In this connection, we now show that the customarily highly endothermic ionization of neutral ethers, viz. $ROCHR'R''$, is substantially facilitated by prior coordination of the oxygen atom to Ag^+ in anhydrous benzene solution.[6,7] There has been found the expected dependence of ease of methoxyl ionization on structural features and, for this reason, attention has been given primarily at this time to cyclopropylcarbinyl and benzhydryl systems. Because many molecular types fall into the first of these general structural classes,

(1) Part XXIII of the series dealing with Ag⁺-catalyzed rearrangements. For the previous paper, see L. A. Paquette and G. Zon, *J. Amer. Chem. Soc.*, **96**, 224 (1974).

(2) A preliminary account of a portion of this work has appeared: L. A. Paquette and G. Zon, *J. Amer. Chem. Soc.*, **94**, 5096 (1972).

(3) National Institutes of Health Postdoctoral Fellow, 1972–1973.

(4) (a) For leading references, see D. Bethell and V. Gold, "Carbonium Ions: An Introduction," Academic Press, London, 1967; (b) G. A. Olah and P. v. R. Schleyer, "Carbonium Ions," Vol. I–III, Wiley-Interscience, New York, N. Y., 1969–1972.

(5) (a) V. J. Shiner, Jr., M. W. Rapp, and H. R. Pinnick, Jr., *J. Amer. Chem. Soc.*, **92**, 232 (1970); (b) R. A. Sneen and J. V. Carter, *ibid.*, **94**, 6990 (1972), and earlier papers in this series.

(6) (a) The subject of coordination complexes of silver ions with heteroatoms has been reviewed: C. D. M. Bewerwijk, G. J. M. vander Kerk, A. J. Leusink, and J. G. Noltes, *Organometal. Chem. Rev., Sect. A*, **5**, 267 (1970). (b) See also T. Fueno, O. Kajimoto, T. Okuyama, and J. Furukawa, *Bull. Chem. Soc. Jap.*, **41**, 785 (1968); (c) D. Gray, R. A. Wies, and W. D. Closson, *Tetrahedron Lett.*, 5639 (1968); (d) B. Franzus, W. C. Baird, E. I. Snyder, and J. H. Surridge, *J. Org. Chem.*, **32**, 2845 (1967); (e) C. F. Wilcox, Jr., and W. Gaal, *J. Amer. Chem. Soc.*, **93**, 2453 (1971).

(7) (a) Rhodium-catalyzed rearrangements of epoxides and oxetanes are known: R. Grigg and G. Shelton, *Chem. Commun.*, 1247 (1971); (b) R. Grigg, R. Hayes, and A. Sweeney, *ibid.*, 1248 (1971); (c) G. Adames, C. Bibby, and R. Grigg, *ibid.*, 491 (1972).