

Theoretical Determination of Molecular Structure and Conformation. XI. The Puckering of Oxolanes

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Abstract. Structural, conformational and energetic properties of cyclopentane (**1**) and the seven oxolanes monoxolane (**2**), 1,3-dioxolane (**3**), 1,2-dioxolane (**4**), 1,2,4-trioxolane (**5**), 1,2,3-trioxolane (**6**), tetroxolane (**7**), and pentoxolane (**8**) are investigated employing the polarized 6-31G* basis set at the Hartree-Fock level of theory. Extensive geometry optimization is carried out within the model of the semirigid pseudorotor. The conformational potentials V of compounds **1-8** are evaluated as a function of the puckering amplitude q and the pseudorotation phase angle ϕ . Ring molecules **1** and **8** are free pseudorotors, while pseudorotation is hindered by barriers ≤ 3.3 kcal/mol for oxolanes **2-7**. Puckering and inversion barriers increase with the number of O-O bonds but decrease with the number of ether bridges. Puckered C_2 -symmetrical twist forms are the most stable conformations for compounds **2-7** but **6**, where highest stability is found for the C_1 -symmetrical envelope forms. At room temperature a multitude of conformers of **1-8** coexists either because of free pseudorotation (barriers < RT) or large amplitudes of pseudolibration. These results are rationalized in terms of the rotor potentials of appropriate reference compounds (C_2H_6 , CH₃OH, H₂O). A more elegant approach leads to a simple π electron count and an analysis of bonding and antibonding overlap in the π -type HOMO's. In this way the effects of substituents can be predicted and conformational preferences of the furanose ring in nucleotides, nucleosides and carbohydrates explained. The relative stability of the oxolanes is analyzed by calculating O-O bond energies, bond-bond interactions and ring strain for each compound. The lability of the higher oxolanes is traced back to increased ring strain. A new method of the conformational analysis of ring compounds is outlined.

INTRODUCTION

The conformational flexibility of saturated five-membered rings is a well established fact.¹ Experimental and theoretical evidence has revealed that cyclopentane (**1**) is puckered and undergoes free pseudorotation.^{2,3} The degree of puckering and the pseudorotational potential change if one or more hetero atoms are incorporated into the framework of the ring. The relationship between the changes of the conformational behaviour of the ring and the electronic nature of the hetero atom has been investigated in some cases^{3,4} but is generally unknown for five-membered rings with three or more hetero atoms.¹

In this work we investigate structural, conformational, and energetic changes caused by progressively replacing CH₂ groups of **1** by O atoms. This leads to the seven possible oxolanes, namely monoxolane (tetrahydrofuran) (**2**), 1,3-dioxolane (**3**), 1,2-dioxolane (**4**), 1,2,4-trioxolane (final ozonide) (**5**), 1,2,3-trioxolane (primary ozonide) (**6**), tetroxolane (**7**), and pentoxolane (**8**). Rings **1**, **2**, and **3** are common building blocks in biologically important compounds like steroids (D ring), prostaglandins, cyclitols, carbohydrates, nucleosides and nucleotides. The overall shape of these molecules is determined by the combined effects of a large number of factors including the parameters which govern pseudorotation of the five-membered rings. It is an interesting question whether the conformational features of **1**, **2**, and **3** are partially retained in these compounds or completely concealed by substituent-substituent interactions. It is one of the objectives of the present work to deal with this question.

The cyclic polyoxides **4**, **5**, and **6** are known to occur as relatively unstable intermediates in reactions of ¹O₂ or O₃ with alkenes.^{5,6} For example, the immediate precursors of the prostaglandins, formed during their biosynthesis from fatty acids, contain the 1,2-dioxolane ring.⁵ An important reaction in atmospheric and solution-phase chemistry is the cycloaddition of ozone to alkenes (ozonolysis) leading to a variety of products via derivatives of the ozonides **5** and **6**. The course of the ozonolysis depends on the properties of the ozonides, which has been subject of many experimental and theoretical studies.^{6,7} In the same context, oxolane **7** has been discussed as a possible cycloaddition product of aldehyde and ozone.⁸ So far there is no evidence indicating the existence of **8**, which could be formed from ¹O₂ and O₃.

In two previous attempts we have tackled the problem of the conformational analysis of five-membered rings.^{3,4} Based on these preliminary investigations we develop in this work a method which leads to a rationalization of the conformational tendencies of compounds **1-8** in terms of orbital interactions. The method is based on the definition of a conformational model for puckered rings, the quantum chemical calculation of the conformational potential V and its analysis with the aid of molecular orbital (MO) theory. By relating puckering and stability to the distribution of π -charge in planar oxolanes a procedure is developed which leads to a simple π -electron count. The advantages of the MO approach are outlined against the background of a conventional molecular mechanics description of the oxolanes. In

addition, a short discussion of substituted oxolanes and their conformation in natural products (see above) is included. Finally, the stability of compounds 1-8 is analyzed in terms of bond-bond interactions and ring strain utilizing calculated energies and stabilities of suitable reference compounds.

CONFORMATIONAL MODEL

The equilibrium geometry of a N -membered ring $X_N Y_M$ with M atoms (substituents) attached to the ring is determined by $3N + 3M - 6$ geometrical parameters. When studying a conformational process of the molecule $X_N Y_M$, the number of calculations becomes excessively high, as $3N + 3M - 7$ parameters have to be determined at K points along a predetermined path in the total configurational space. However, the number of computations may be reduced if a suitable conformational model is selected. For alicyclic rotor molecules this is done by defining the rigid and semirigid rotor model (Table 1). The total $3N - 6$ ($3N + 3M - 6$) dimensional space is mapped onto a $N - 3$ dimensional conformational space, which is spanned by $N - 3$ dihedral angles.

At a first approximation, the conformational potential V of $X_N Y_M$ is calculated as a function of the subspace coordinates keeping the remaining coordinates fixed at standard values (rigid rotor model).⁹ This approach is improved by optimizing those parameters, which couple with the conformational coordinates, for each conformer considered in the $N - 3$ dimensional subspace. Thus, semirigid rotor models of the molecule $X_N Y_M$ are obtained. For small molecules, conformational barriers calculated with these models differ only slightly from barrier values evaluated with the fully flexible rotor (optimization of $3N - 7$ or $3N + 3M - 7$ parameters).¹⁰

The conformational space of a N -membered ring is also of dimension $N - 3$, spanned by $N - 3$ ring puckering coordinates.¹¹ It can be partitioned into $(N - 3)/2$ (N odd) or $(N - 4)/2$ (N even) pseudorotational two-dimensional subspaces and one (N even) inversional one-dimensional subspace.¹² A pseudorotational subspace is spanned by the puckering amplitude q ($q > 0$) and the pseudorotation phase angle ϕ ($0 \leq \phi < 360^\circ$), describing degree and mode of ring puckering.¹¹

In the case of the oxolanes, just one (q, ϕ) -pair has to be considered. The conformational potential $V =$

$V(q, \phi)$ can be expanded as a Fourier series in the phase angle ϕ ,

$$V(q, \phi) = \sum_{k=0}^{\infty} \{V_k^c(q) \cos k\phi + V_k^s(q) \sin k\phi\} \quad (1)$$

with V_k^c and V_k^s being expanded in a Taylor series

$$V_k(q) = \sum_{l=0}^{\infty} V_{kl} q^l \quad (2)$$

In previous work³ we have shown that for five-membered rings with C_{2v} -symmetrical planar forms the potential V can be approximated by Eq. (3):

$$V(q, \phi) = V_{02} q^2 + V_{04} q^4 + V_{22} q^2 \cos 2\phi + V_{24} q^4 \cos 2\phi \quad (3)$$

where V_{00} has been taken as the energy zero.

Since the internal ring angles couple strongly with the puckering parameters, application of a rigid pseudorotor model for the evaluation of the potential V leads to erroneous results. The description of conformational processes in puckered rings requires the definition of a semirigid pseudorotor model. For each given set of puckering coordinates, $N - 3$ internal ring angles have to be optimized (Table 1). Also, the optimization of N internal ring bond lengths becomes important if ring molecules with strong bond-bond interactions are considered.⁴ In cyclic molecules $X_N Y_M$ with bulky substituents Y , substituent-substituent interactions influence the degree and the mode of ring puckering. Then, the evaluation of V requires in addition the optimization of all substituent orientation angles for each conformer considered.^{12,13}

Although the use of the puckering parameters facilitates the *ab initio* description of conformational interconversions in puckered rings tremendously, the computational task is considerably more complicated than that required to describe alicyclic rotor molecules. This is not only due to the necessity of applying semirigid pseudorotor models, but also due to the fact that elaborate basis sets, augmented by at least one set of polarization functions in the heavy atom basis sets, are indispensable to give a reliable account of puckering amplitude and conformational barriers for nonplanar rings by HF theory.^{4,14,15} The importance of polarization functions is even enhanced if the conformation of per- or polyoxides

Table 1. Conformational Models of Alicyclic Rotor and Cyclic Pseudorotor Molecules

Molecule ^a	Rotor parameters			Parameters to be optimized	Pseudorotor parameters			Parameters to be optimized
	Number	Type	Model		Number	Type	Model	
X_N	$N - 3$	dihedral angles	rigid rotor	0	$N - 3$	puckering coordinates		
	$+ N - 2$	chain bond angles	semirigid rotor	$N - 2$	$+ N - 3$	internal ring angles	semirigid pseudorotor	$N - 3$
	$+ N - 1$	chain bond lengths	flexible rotor	$2N - 3$	$+ N$	internal bond lengths	flexible pseudorotor	$2N - 3$
$X_N Y_M$	$+ 2M$	external angles	semirigid rotor	$N - 2 + 2M$	$+ 2M$	external angles	semirigid pseudorotor	$N - 3 + 2M$
	$+ M$	external bond lengths	flexible rotor	$2N - 3 + 3M$	$+ M$	external bond lengths	flexible pseudorotor	$2N - 3 + 3M$

a. N atoms X form the chain or ring. M atoms Y are attached to the chain or the ring.

has to be determined.^{16,17} On the other hand, an accurate description of conformation and conformational changes does not necessarily imply that all geometrical parameters have to be calculated at the highest level of basis set sophistication. In previous investigations we have shown that reasonable O–O bond lengths are found with a split valence basis due to a cancellation of basis set and correlation effects.^{16,18}

Due to the reasons outlined above, the following procedure is used to calculate the conformational potential V for compounds 1–8 with the aid of restricted HF theory. First, the ring atoms of each molecule are numbered utilizing the C_{2v} symmetry of the planar forms of 2–7 (Fig. 1). This leads to C_1 and C_2 symmetry for conformers with $\phi = 0$ or 180° and 90 or 270° , respectively. Henceforth, these conformers are called envelope (E) and twist (T) form. Preliminary calculations are carried out with the minimal STO-3G basis set (basis A)¹⁹ fixing the phase angle ϕ in multiples of $\pi/10$.

At the second stage of the investigation the split-valence 4-31G basis (B)²⁰ is employed in order to determine the dependence of bond distances and internal bond angles on q and ϕ for those oxolanes, which contain the O–O linkage. For compounds 1, 2, and 3 only the internal ring angles are optimized while the bond lengths are kept at standard values ($r(\text{CC}) = 154$ pm,

$r(\text{CO}) = 143$ pm)²¹ for all conformers considered. In all calculations the geometry of the CH_2 groups is chosen to preserve local C_{2v} symmetry with the H–C–H angle and the C–H bond length being 109.5° and 109 pm, respectively.

At the third stage of the investigation the optimization of internal ring angles is repeated employing the 6-31G* basis (C) which contains 6 d functions in each of the heavy atom sets.²² At this stage all other parameters are held at either basis B or standard values. Final HF/C energies lead to the evaluation of $V(q, \phi)$ for 1–8.

Results obtained by this procedure are summarized in Tables 2, 3, and 4. Table 2 contains absolute and relative HF/C energies computed for those conformers of compounds 1–8, which are located at the stationary points of the potential V . The corresponding geometries are listed in Table 3. The coefficients V_{ki} of the expansion (3) of the theoretically determined potential $V(q, \phi)$ are shown in Table 4. Figure 2 displays the calculated potentials V for 1–8 in the form of energy contour line diagrams. These diagrams may be viewed in connection with Fig. 1 where puckered conformers of 2 are drawn at intervals of $\pi/10$ along an assumed pseudorotation itinerary. The most favorable pseudorotation path follows the energy valleys of a conformational surface. It is indicated in the contour line diagrams of Fig. 2 by a dashed line.

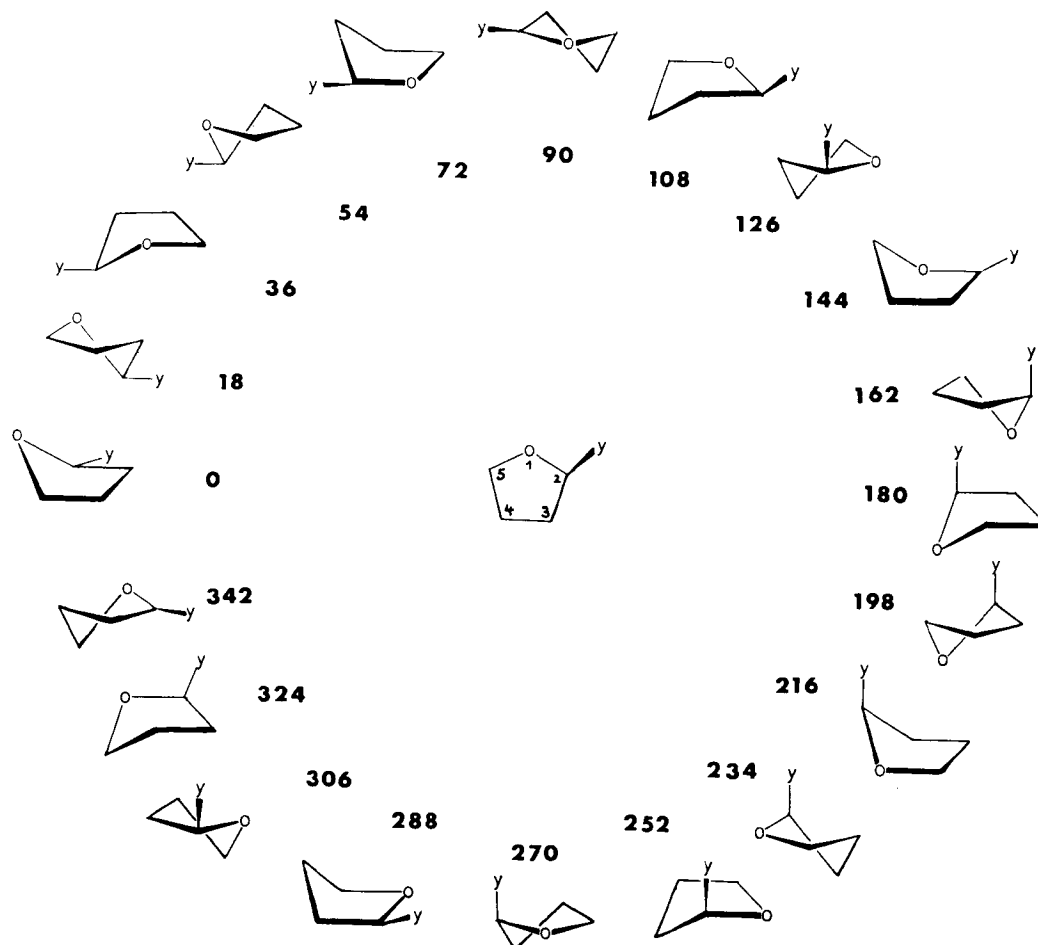


Fig. 1. Pseudorotation itinerary of a substituted oxolane. The numbering of the ring atoms is based on the C_{2v} symmetry of the unsubstituted ring.

Table 2. Total Energies (hartrees) and Relative Energies (kcal/mol) of Cyclopentane (1) and Oxolanes 2-8 Obtained for Geometries with the 6-31G* Basis

Molecule	Pseudorotation angle ϕ , deg	Symmetry	Absolute	Relative
Cyclopentane (1)	planar	D_{5h}	-195.15347	4.77
	0	C_5	-195.16106	0.01
	90	C_2	-195.16107	0
Oxolane (2)	planar	C_{2v}	-230.96842	3.45
	0	C_2	-230.97273	0.74
	90	C_2	-230.97391	0
1,3-Dioxolane (3)	planar	C_{2v}	-266.78512	2.17
	0	C_2	-266.78733	0.79
	90	C_2	-266.78858	0
1,2-Dioxolane (4)	planar	C_{2v}	-266.68820	5.68
	0	C_2	-266.69370	2.23
	90	C_2	-266.69726	0
1,2,4-Trioxolane (5)*	planar	C_{2v}	-302.50567	6.28
	0	C_2	-302.51042	3.30
	90	C_2	-302.51567	0
1,2,3-Trioxolane (6)*	planar	C_{2v}	-302.40996	7.88
	0	C_2	-302.42252	0
	90	C_2	-302.41769	3.03
Tetroxolane (7)	planar	C_{2v}	-338.12544	10.86
	0	C_2	-338.13868	2.55
	90	C_2	-338.14275	0
Pentoxolane (8)	planar	D_{5h}	-373.73968	17.38
	0	C_5	-373.76738	0
	90	C_2	-373.76731	0.04

a. Energies from Ref. 4.

CONFORMATIONAL FEATURES

The computed conformational data are in fair agreement with relevant experimental observations on compounds 1-6 as can be seen by inspecting Table 5 where experimental q , ϕ , and ΔE values are summarized.²³⁻³⁶ All oxolanes prefer nonplanar conformations. The planar forms are located at a local maximum of the conformational surface (center of contour line diagrams of Fig. 2). The degree of puckering of the most stable forms depends on both the number of O-O and epoxide linkages incorporated into the ring framework. As shown in Fig. 3 the optimum value of the puckering amplitude q increases almost linearly with the number of O-O bonds in the ring, the largest value being calculated for 8 ($q = 53$ pm). If, however, the number of ether linkages in the ring is increased, a lowering of q is observed.

Since V is a function of q^2 (and q^4), the barriers to planarity also show a strong dependence on the number of O-O bonds varying from about 5 (1) to 17 kcal/mol (8). In the series 1, 2, 3 the barrier to planarity decreases to about 2 kcal/mol (Fig. 3) indicating its dependence on the number of ether oxygen atoms in the ring.

For all oxolanes the conformational mode with the lowest energy barrier is pseudorotation. According to the symmetry of planar 1 and 8 (D_{5h}) the first ϕ -dependent terms in Eq. (1) are $V_{10}(q)\cos 10\phi$. Calculations reveal that any contributions to V resulting from these terms are very small. Thus, a reasonable approximation for V is given by the first two terms of Eq. (3) (see Table 4),

$$V = V_{02}q^2 + V_{04}q^4. \quad (4)$$

Equation (4) describes the potential of a free

pseudorotor. As shown in Fig. 2 contour lines of such a potential are concentric with regard to the origin of the q , ϕ coordinate system.

Pseudorotation becomes hindered when O atoms are incorporated into the ring. For 2 and 3 barriers of 0.7 and 0.8 kcal/mol are obtained, which are probably too high by 0.6-0.7 kcal/mol (see Table 5) due to the use of fixed bond lengths. One or more peroxide groups increase the pseudorotational barriers to 2-3 kcal/mol (compounds 4-7). This is reflected by the contour line diagrams of Fig. 2, in particular by the form of the calculated pseudorotation paths. It is concentric for 1 and 8 but elliptic for the hindered pseudorotor molecules 2-7. We define the ellipticity of the pseudorotational path by $\epsilon = q_T/q_E - 1$, where q_T and q_E are the q values of the most stable T and E forms, respectively. Calculated values of ϵ are given along with the pseudorotational barriers and other conformational parameters in Table 6.

For free pseudorotors q is independent of ϕ which implies $\epsilon = 0$ for 1 and 8. By inspection of the contour line diagrams of V (see also Table 3) it becomes obvious that the largest q value is found for the most stable conformation. Accordingly, $\epsilon > 0$ is obtained in those cases where the T forms at 90° and 270° correspond to the energy minima and the E forms at 0° and 180° to the saddle points of the conformational surface respectively. A value $\epsilon < 0$ is indicative of the reverse situation (compound 6). The data in Table 6 reveal that the pseudorotational barriers increase with the magnitude of ϵ .

It is interesting to note that for all oxolanes the calculated pseudorotation barriers are comparable or

Table 3. Geometrical Parameters for Cyclopentane (1) and Oxolanes 2-8^a

Molecule	q	r_1	r_2	r_3	α_1	α_2	α_3	τ_1	τ_2	τ_3
A. Planar forms										
1	0	154*	154*	154*	108	108	108	0	0	0
2	0	143*	154*	154*	112.2	108.2	105.7	0	0	0
3	0	143*	143*	154*	108.3	110.1	105.8	0	0	0
4	0	153.9	143.8	146.6	104.4	108.1	109.7	0	0	0
5	0	141.7	144.1	146.9	109.9	107.8	107.2	0	0	0
6	0	146.3	143.2	154.2	108.6	108.8	106.9	0	0	0
7	0	143.3	145.5	147.4	108.9	108.4	107.2	0	0	0
8	0	146.0	146.0	146.0	108.0	108.0	108.0	0	0	0
B. Envelope forms with $\phi = 0^\circ$ or 180°										
1	40.3	154*	154*	154*	102.6	104.1	106.3	39.2	24.3	0
2	36.2	143*	154*	154*	105.7	105.5	103.9	38.9	23.0	0
3	30.0	143*	143*	154*	106.0	106.5	105.1	32.6	19.6	0
4	37.3	152.9	143.7	147.8	100.1	105.0	107.5	36.3	23.5	0
5	35.0	141.5	143.9	147.6	103.4	105.8	105.0	37.6	23.1	0
6	47.0	145.4	143.7	155.1	101.3	102.3	104.1	48.9	29.5	0
7	44.9	142.0	145.9	149.5	103.6	101.3	104.6	48.0	28.4	0
8	53.2	143.8	146.0	148.7	98.1	100.6	103.6	54.6	33.4	0
C. Twist forms with $\phi = 70^\circ$ or 270°										
1	40.5	154*	154*	154*	106.7	105.3	103.0	12.9	33.6	41.4
2	37.0	143*	154*	154*	110.7	106.2	101.6	12.0	30.6	36.2
3	32.1	143*	143*	154*	107.9	107.7	102.7	11.4	27.6	33.7
4	45.1	154.3	143.9	146.1	101.6	104.8	102.3	15.2	39.7	50.2
5	44.7	142.6	143.3	146.7	105.8	105.4	100.2	15.3	39.0	47.4
6	41.6	147.4	143.3	151.8	106.6	105.0	101.9	14.3	35.5	44.6
7	48.9	144.1	145.4	144.7	106.8	102.9	99.8	16.2	42.3	52.3
8	53.5	147.8	144.6	143.7	104.0	102.3	98.7	17.6	46.4	57.9

a. Distances in pm, angles in deg. Starred values have not been optimized. Values of r have been obtained at the HF/4-31G, all other geometrical parameters at the HF/6-31G* level. The geometrical parameters of planar, E or T forms are defined in the following way (X, Y, Z = CH₂ or O):

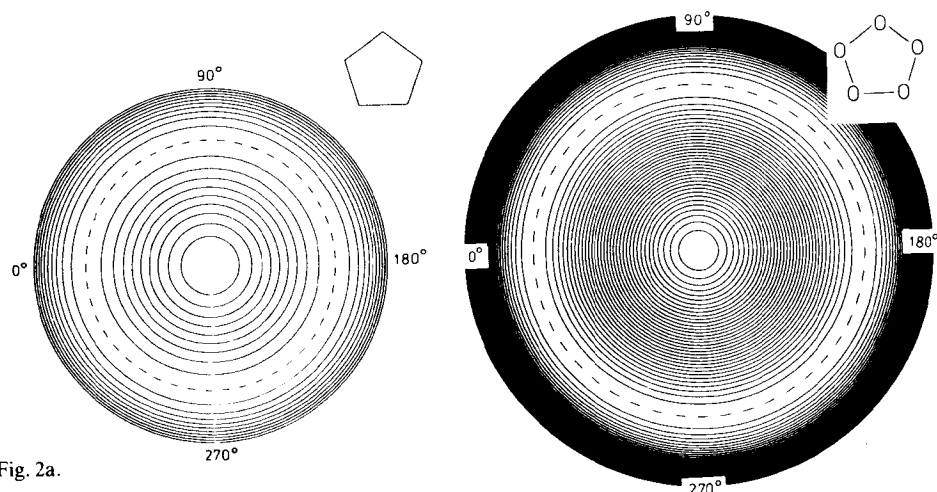
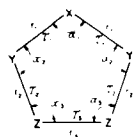


Fig. 2a.

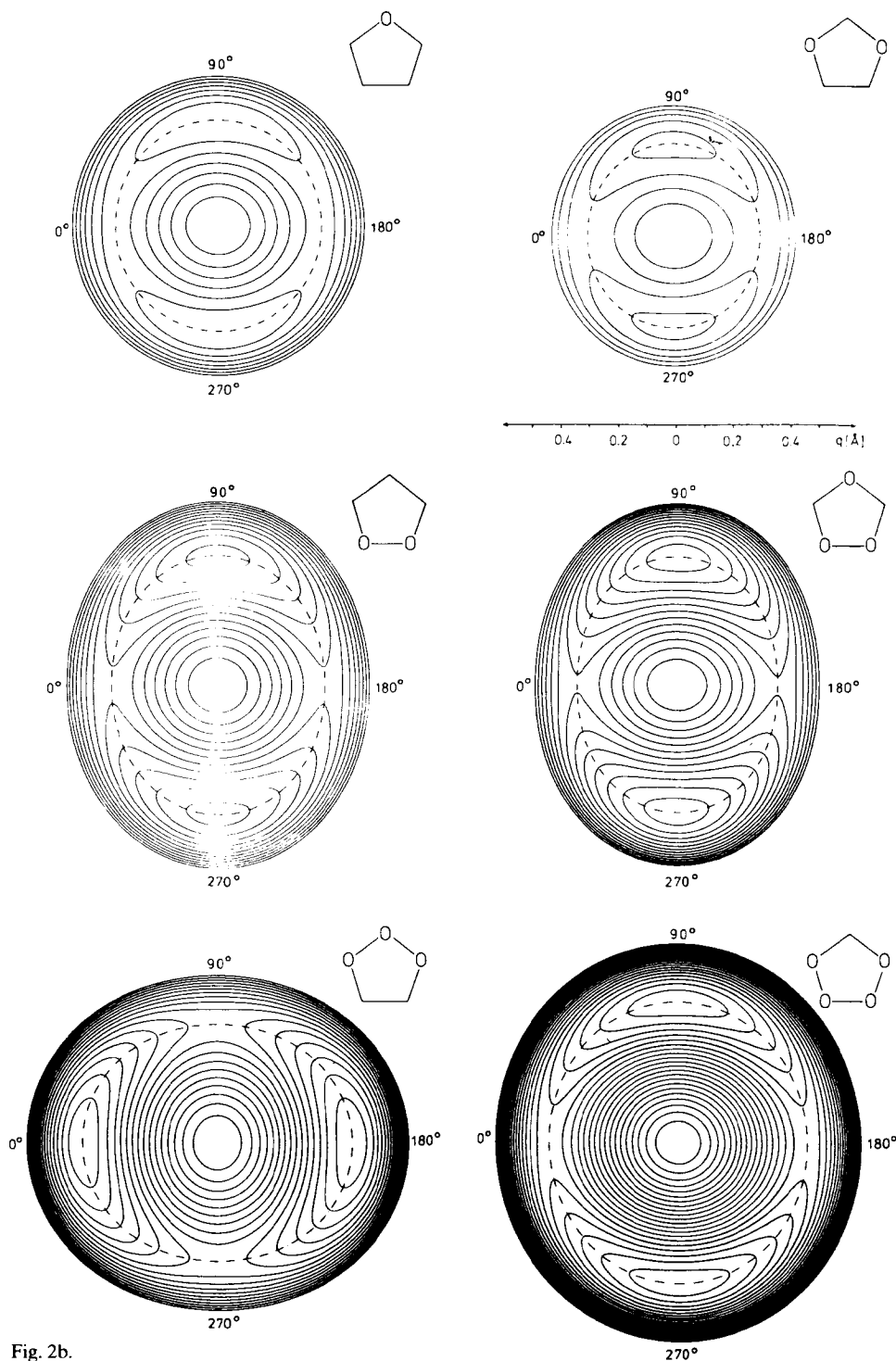


Fig. 2a. Potential surfaces of compounds 1 and 8, and b. 2-7. The potential is zero at the center of the (q, ϕ) -diagram. It decreases towards the dashed line but increases beyond this line. The vertical spacing of two successive contour lines is 0.5 kcal/mol. The dashed lines indicate the most favorable pseudorotation paths.

Table 4. Potential Coefficients V_{ki} ($\times 10^3$) for Cyclopentane (1) and Oxolanes 2–8 Calculated From Eq. (2)^a

Molecule	V_{02}	V_{04}	V_{22}	V_{24}	Minimum
1	-5.81	0.00177	—	—	free pseudorotor
2	-4.59	0.00171	0.46	-0.00014	C_2
3	-3.75	0.00199	1.08	-0.00069	C_2
4	-5.27	0.00158	0.30	0.00021	C_2
5	-5.58	0.00178	0.72	0.00020	C_2
6	-6.38	0.00162	-0.77	0.00000 ₁	C_2
7	-8.65	0.00197	0.42	0.00007	C_2
8	-12.14	0.00212	—	—	free pseudorotor

a. V_{00} is taken to be the energy of the planar form.

Table 5. Experimental Evidence on the Puckering in Cyclopentanes and Oxolanes

Molecule	ϕ^* (deg)	q^* (pm)	PB; IB* (kcal/mol)	Method ^b	Ref.
1	free pseudorotation	43; 46	0; 5.2	TC, NMR, ED, R	2, 23, 24
2	90, 270	38	0.1	ED, MW, Far-IR	25, 26
3	0, 180	38	0.1	Far-IR, MW	27, 28
4	90, 270	45 ^d		PE, MW	29
5	90, 270	46		MW	30
6	0, 180			IR	31
Substituted molecules ^c					
Cyclopentanes	unspecified	30–42 (4)		X-ray	32, 33
D-Ring					
Esterones	36–54 (19)	40–50 (28)		X-ray	32, 34
Furanose ring					
Nucleosides } Nucleotides }	108 ± 18 (30) 252 ± 18 (14)	30–45 (55)		X-ray	32, 35
Carbohydrates	90–108 (3) 252–270 (6)	30–42 (11)		X-ray	32, 33

a. Phase angle, puckering amplitude, pseudorotational barrier (PB) and inversion barrier (IB) of stable conformation.

b. TC — thermochemical; ED — electron diffraction; R — Raman; MW — microwave; IR — infrared; PE — photoelectron spectroscopy.

c. Number of molecules which possess q, ϕ -values in the specified range are given in parentheses.

d. The dihedral angle at the peroxide bridge has been found to be $50 \pm 2^\circ$ by MW spectroscopy.^{29c} The q value has been derived from the parameters given in Ref. 29c.

smaller than the experimentally observed barrier to internal rotation for ethane (2.9 kcal/mol).¹⁰ Thus compounds 1–8 are highly flexible on the time scale of most chemical processes,^{*} which is of importance when analyzing the stereochemistry of reactions where oxolanes are involved as reaction intermediates.^{5,7}

At room temperature a multitude of conformers coexists since both q and ϕ oscillate about their equilibrium values, a process which has been termed pseudolibration.³⁶ The amplitudes of pseudolibration can be estimated from calculated values q_{\min} , q_{\max} , Δq and $\Delta\phi$ listed in Table 6. For an external heat content of RT , values $q_{\min} \leq q \leq q_{\max}$ and $\phi \pm \Delta\phi$ are possible. Pseudolibration degenerates to pseudorotation if the barrier values are lower than RT .

It is interesting to note that q values of furanose rings obtained by X-ray measurements for nucleosides, nucleotides and carbohydrates predominantly fall into the range of values between q_{\min} and q_{\max} of 2. Obviously, substituent–substituent and substituent–ring interactions are such that significant flattening or enhanced puckering

of the ring are avoided. This is also true for other substituted oxolanes (Table 5).

We now investigate the effects which cause ring puckering, first employing a molecular mechanics approach and then a MO description of puckering.

Molecular Mechanics Description of Puckering

The puckering of cyclopentane has been rationalized in terms of torsional (Pitzer) and bond angle (Baeyer) strain, the former being large in the planar form, the latter increasing with enhanced puckering.² The optimal puckering amplitude is the result of a minimization of both Pitzer and Baeyer strain. For rings with hetero atoms like O, the classical strain model is extended either by using the concepts of electron lone pair–lone pair or of electron lone pair–bond pair repulsions. If the oxygen

* On an infrared, microwave, electron diffraction or X-ray time scale the behaviour of compounds 4–7 should be predictable so that properties similar to those of more rigid species should be exhibited.

Table 6. Conformational Parameters Calculated for Compounds 1-8

Molecule	q^a (pm)	PB ^b (kcal/mol)	ϵ^c	$q_{min}^{RT,d}$ (pm)	$q_{max}^{RT,d}$ (pm)	$\Delta q^{RT,d}$ (pm)	$\Delta\phi^{RT,d}$ (deg)	SEP ^e (kcal/mol)
1	40.5	0	0	32.0	48.9	16.9	± 180	11.0
2	37.0	0.7	0.02	28.0	45.0	17.0	$\pm 180^f$	9.3
3	32.1	0.8	0.07	20.5	37.9	17.4	$\pm 180^f$	9.7
4	45.1	2.2	0.21	37.2	51.8	14.6	± 26	12.0
5	44.7	3.3	0.28	36.2	53.7	17.5	± 21	21.3
6	47.0	3.0	-0.11	39.6	53.8	14.2	± 25	20.7
7	48.9	2.5	0.09	42.9	54.1	11.2	± 27	39.7
8	53.5	0	0.01	47.8	59.1	11.3	± 180	65.7

a. Puckering amplitude of most stable conformation.

b. Pseudorotational barrier.

c. Ellipticity of conformational potential V measured by $\epsilon = q_r/q_e^{-1}$. Negative values are indicative of global minima at $\phi = 0$ and 180° . See text.

d. Values of q_{min}^{RT} , q_{max}^{RT} , Δq^{RT} and $\Delta\phi^{RT}$ indicate in which part of conformational space pseudolibration of the ring takes place at room temperature (external heat content is RT). If $\Delta\phi = \pm 180^\circ$, the external heat content is sufficient for pseudorotation to take place.

e. Strain energies of planar forms.

f. The calculated values of $\pm 64^\circ$ (2) and $\pm 59^\circ$ (3) are not very likely since the HF/C pseudorotational barriers are overestimated due to the use of standard bond lengths.

lone pairs are localized in sp^3 -hybridized orbitals, pair-pair repulsions will be largest in the planar oxolane forms, thus leading to puckering.

In order to get a qualitative idea on the degree and mode of puckering, the rotational barriers of the three alicyclic rotor molecules ethane (2.9),¹⁰ methanol (1.1)¹⁰ and hydrogen peroxide (7.5 kcal/mol, *cis* barrier)¹⁶ are

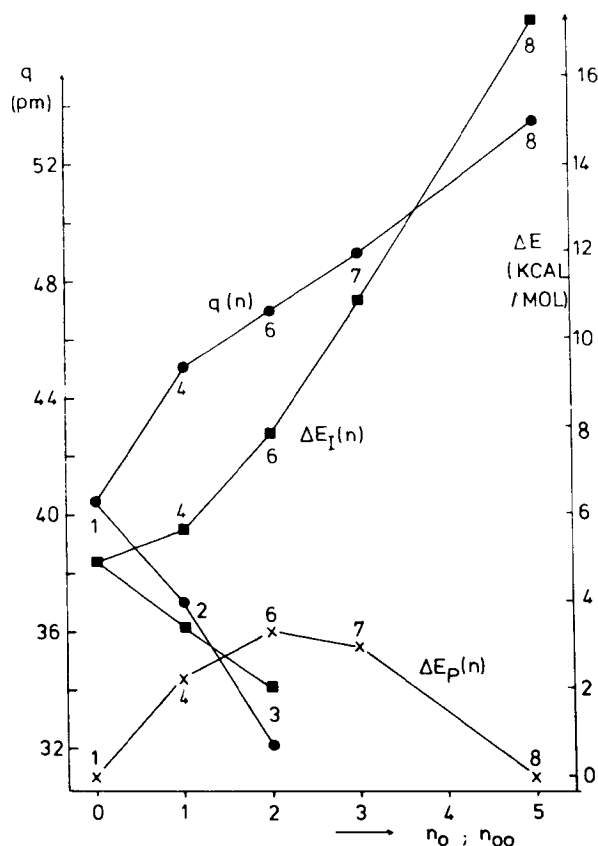


Fig. 3. Dependence of the puckering amplitude q (●), the inversion barriers ΔE_I (■) and the pseudorotational barriers ΔE_P (×) on the number n of O-O bonds or epoxide bridges.

compared. According to these values, Pitzer strain should be largest at a peroxide, smallest at an epoxide bridge of a planar oxolane. These assumptions are the basis of the molecular mechanics analysis presented in Fig. 4, where the parts of the ring with high Pitzer strain are marked in each molecule. A particular mode of puckering leads to a favorable overall stabilization of the molecule if the highest torsion is distributed at the corresponding ring bonds. In Table 7 the ring angles of a regular pentagon are given for infinitesimal and finite puckering according to formulas first derived by Dunitz.³⁷ Thus, $\phi = 0^\circ$ (180°) implies $\tau_1 > \tau_2 > \tau_3$ and

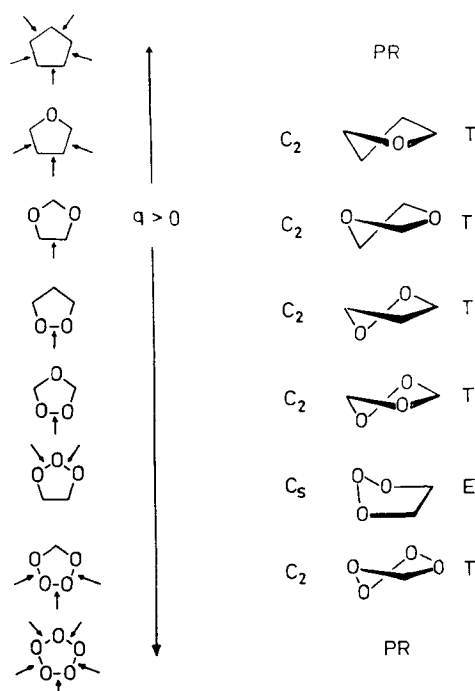


Fig. 4. Molecular mechanics analysis of the puckering in compounds 1-8. Arrows point to bonds with high torsional strain. Maximum reduction of strain is predicted for the conformations shown on the right-hand side (PR-free pseudorotation).

Table 7. Internal Ring Angles α , and τ_i for Infinitesimal and Finite Out-of-plane Displacements of a Regular Pentagon ($\alpha = 108^\circ$)^a

Angle	Formulas for q (infinite) ^a		Estimated values for $q = 20$ pm	
	$\phi = 0^\circ$	$\phi = 90^\circ$	$\phi = 0^\circ$	$\phi = 90^\circ$
α_1	$3\pi/5 - 0.0001802 q^2$	$3\pi/5 + 0.0000100 q^2$	108-4.1	108 + 0.2
α_2	$3\pi/5 - 0.0001145 q^2$	$3\pi/5 - 0.0000557 q^2$	108-2.6	108 - 1.3
α_3	$3\pi/5 - 0.0000081 q^2$	$3\pi/5 - 0.0001620 q^2$	108-0.2	108 - 3.7
τ_1	$0.02689 q$	$0.00874 q$	33.1	10.0
τ_2	$0.01662 q$	$0.02289 q$	19.0	26.2
τ_3	0	$0.02828 q$	0	32.4

a. Formulas according to Dunitz, Ref. 37. The amplitude q is given in pm. Angles for infinitesimal puckering in radians, for finite puckering in deg.

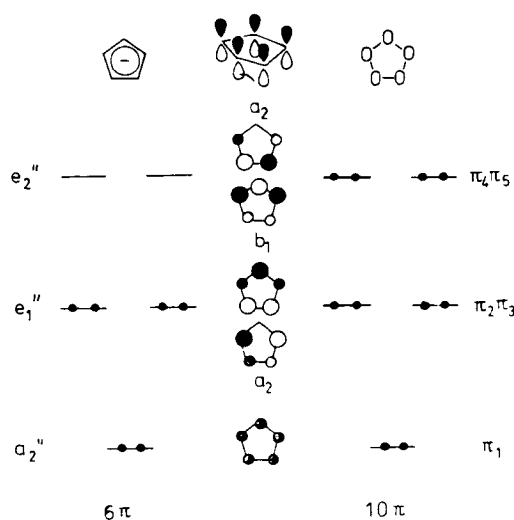


Fig. 5. π -Molecular orbitals of cyclopentadienyl anion and pentoxolane. Symmetry notations are given both for D_{5h} and C_{2v} symmetry.

$\phi = 90^\circ$ (270°) $\tau_3 > \tau_2 > \tau_1$. Using this piece of information maximum stability is predicted for the T and E forms presented in Fig. 4.

Although the molecular mechanics approach successfully describes conformational features of 1-8 in terms of appropriate single rotor potentials, it lacks any insight into the interplay between electronic structure and puckering.

Molecular Orbital Description of Puckering

Many successful attempts have been made to relate stability or instability of molecules to the number of π -electrons present.³⁸ For example, the aromatic character of the cyclopentadienyl anion (CPA) is associated with the fact that it possesses an ensemble of 6π -electrons. The π -electrons occupy the three bonding π -MO's while the antibonding π -MO's remain unoccupied (Fig. 5). This is considered to lead to overall stabilization of CPA.

For planar pentoxolane the same number and ordering of π -MO's is obtained (Fig. 5). Each O atom contributes two electrons to the π -set, thus leading to a total of 10π -electrons, which occupy not only the bonding but also the antibonding π -MO's. Therefore, a 10π -electron configuration causes destabilization of planar 8.

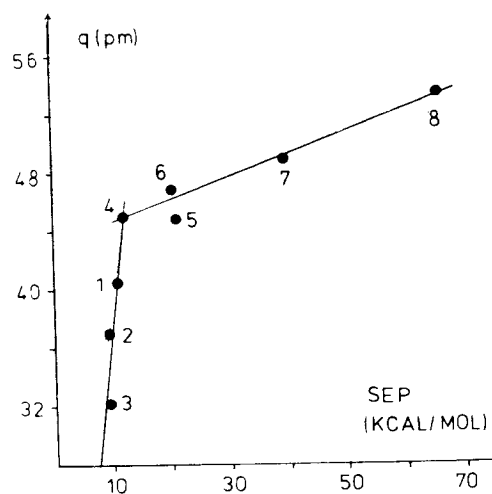


Fig. 6. Relationship between puckering amplitude q of the most stable conformation and strain energy of planar forms (SEP).

The π -MO diagram of Fig. 5 can also be applied to the planar forms of other oxolanes. The methylene groups can interact via their pseudo- π -orbital with the $2p\pi$ -orbitals of the O atoms. Each CH_2 group contributes two electrons to the π -set. Accordingly, all planar oxolanes possess the unfavorable π -electron decet. However, the extent of π -electron delocalization is different for the oxolanes. The pseudo- π -orbitals of 1-7 extend radially away from the ring similar to the π -orbitals of [5]-radialene. From theoretical and experimental investigations it is known that π -delocalization is small in the radialenes.^{39,40} Destabilizing interactions result predominantly from the cis arrangement of the exocyclic double bonds and are thus reduced if a $\text{C}=\text{CH}_2$ unit is replaced by an O atom.

If the oxolane ring puckers, antibonding overlap in the a_2 and b_1 HOMO (Fig. 6) is lowered. The MO's mix with σ MO's of appropriate symmetry and become stabilized. The mode of puckering determines which of the two antibonding HOMO's is more stabilized. From the formulas of Table 7 and the form of the HOMO's it is easy to see that E-type puckering lowers the b_1 MO and T-type puckering the a_2 MO. This is confirmed by the calculated orbital energies listed in Table 8.

Table 8. Absolute and Relative Orbital Energies of the Two Highest Occupied MO's of Compounds 1-8^a

Molecule	ϕ , deg	Orbital energies (character) ^b		Stabilization of HOMO's ^b			Predicted stability
		MO 19	MO 20	b ₁	a ₂	total	
1	planar	-0.4502 (b ₁)	-0.4502 (a ₂)	0	0	0	
	0	-0.4686 (b ₁) ^c	-0.4531 (a ₂)	-11.5	-1.8	-13.3	free
	90	-0.4686 (a ₂) ^c	-0.4533 (b ₁)	-1.9	-11.5	-13.3	pseudorotation
2	planar	-0.4687 (a ₂) ^d	-0.4036 (b ₁)	0	0	0	
	0	-0.4701 (a ₂) ^d	-0.4154 (b ₁)	-7.4	-0.9	-8.3	
	90	-0.4810 (a ₂) ^d	-0.4062 (b ₁)	-1.6	-7.7	-9.3	T forms
3	planar	-0.4387 (a ₂)	-0.4155 (b ₁)	0	0	0	
	0	-0.4391 (a ₂)	-0.4279 (b ₁)	-7.8	-0.2	-8.0	
	90	-0.4437 (a ₂)	-0.4483 (b ₁)	-1.7	-3.1	-4.8	E forms
4	planar	-0.4776 (b ₁)	-0.4088 (a ₂)	0	0	0	
	0	-0.4868 (b ₁)	-0.4135 (a ₂)	-5.8	-2.9	-8.7	
	90	-0.4693 (b ₁)	-0.4321 (a ₂)	5.2	-14.6	-9.4	T forms
5	planar	-0.4479 (b ₁)	-0.4357 (a ₂)	0	0	0	
	0	-0.4658 (b ₁)	-0.4389 (a ₂)	-11.2	-2.0	-13.2	
	90	-0.4610 (a ₂)	-0.4507 (b ₁)	-1.7	-15.9	-17.6	T forms
6	planar	-0.4761 (a ₂)	-0.4297 (b ₁)	0	0	0	
	0	-0.4804 (a ₂)	-0.4527 (b ₁)	-14.7	-2.7	-17.4	
	90	-0.4833 (a ₂)	-0.4372 (b ₁)	-5.0	-4.5	-9.5	E forms
7	planar	-0.4795 (b ₁)	-0.4661 (a ₂)	0	0	0	
	0	-0.5028 (b ₁)	-0.4730 (a ₂)	-14.6	-4.3	-18.9	
	90	-0.4909 (a ₂)	-0.4855 (b ₁)	-3.8	-15.6	-19.4	T forms
8	planar	-0.5108 (b ₁)	-0.5108 (a ₂)	0	0	0	
	0	-0.5396 (b ₁)	-0.5189 (a ₂)	-18.1	-5.1	-23.3	free
	90	-0.5400 (a ₂)	-0.5190 (b ₁)	-5.1	-18.3	-23.3	pseudorotation

a. Absolute energies in hartree, relative energies in kcal/mol.

b. Orbitals are characterized by the symmetry notation appropriate for the planar C_{2v}-symmetrical forms.

c. MO 15.

d. MO 18.

The symmetry of the HOMO of planar 2-7 is determined by the topology of the ring. Oxolanes with an O-O linkage are intersected by the C₂ axis and thus possess an a₂ HOMO (4, 5, 7) while the HOMO of the other oxolanes is of b₁ symmetry (2, 3, 6). For compounds 4-7 the puckering mode which leads to stabilization of the HOMO is preferred. The calculated total lowering of orbital energy of the a₂ and b₁ MO's and the lowering of the energy of the HOMO itself (Table 8) reflect the increase of q with the number of O-O bonds in the ring — the stronger the puckering for the mode the larger the stabilization, and the relative stabilities of E and T forms. The stabilization of the HOMO's is inconsistent with the calculated order of stabilities only in 3 (Table 8). This, however, could be due to the use of standard bond lengths which neglects a ϕ -dependent change in bond-bond interactions (see below).

In previous work we have shown that ozonides 5 and 6 are stabilized by an equatorial CH₃ group but destabilized by an axial CH₃ group.¹³ In the first case, the substituent can act as a π -acceptor due to effective overlap between π -type orbitals. In the latter case π -type overlap is prohibited and the CH₃ group acts predominantly as a σ -donor. If a fluorine atom is attached to the ring, the situation is reversed since F is a π -donor and, hence, destabilizes ozonides 5 and 6 if equatorially positioned.^{7c}

We may expect similar effects in other substituted

oxolanes. For example, preliminary calculations show that hydroxy- and fluoro-oxolanes also prefer conformations with an axial position of the substituent. In methyl-oxolanes, however, the equatorial site is preferred.⁴¹ These observations are in line with results obtained for substituted cyclopentanes.^{1,41,42} Obviously, substituent-ring interactions as described above are the determining factors that govern the conformational features of substituted oxolanes.

One relevant piece of information in this connection is the fact that the furanose conformations found for nucleosides and nucleotides cluster in a relatively narrow range of q , ϕ -space (Table 5). This is unexpected in view of the conformational lability of 2 (Table 6). An analysis of the substituent orientations, however, supports the view that substituent — ring interactions are very similar in these compounds leading to the observed preference of certain ϕ values.⁴¹ Work is in progress to test these findings further.

STRAIN AND STABILITY

Bond separation energies (BSE) of isodesmic reactions* provide measures of the electronic interactions

* The term *isodesmic* denotes a reaction in which there are equal numbers of bonds of a given formal type in both reactants and products.

Table 9. Bond Separation Energies of Molecules 1-8 and Appropriate Reference Compounds

Reaction	Energy ^a	Reference energy ^d
Isodesmic Reactions		
1 + 5CH ₄ → 5CH ₃ CH ₃	-1.5 ^b (6.7; 2.3)	4.7
2 + 4CH ₄ + H ₂ O → 3CH ₃ CH ₃ + 2CH ₃ OH	8.2 ^b (15.8)	14.0
3 + 3CH ₄ + 2H ₂ O → CH ₃ CH ₃ + 4CH ₃ OH	19.0 ^b (19.2)	28.7
4 + 3CH ₄ + 2H ₂ O → 2CH ₃ CH ₃ + 2CH ₃ OH + H ₂ O ₂	7.7	14.0
5 + 2CH ₄ + 3H ₂ O → 4CH ₃ OH + H ₂ O ₂	21.5	36.5
6 + 2CH ₄ + 3H ₂ O → CH ₃ CH ₃ + 2CH ₃ OH + 2H ₂ O ₂	10.8	23.6
7 + CH ₄ + 4H ₂ O → 2CH ₃ OH + 3H ₂ O ₂	10.6	39.4
8 + 5H ₂ O → 5H ₂ O ₂	-1.7	46.6
CH ₃ CH ₂ CH ₃ + CH ₄ → 2CH ₃ CH ₃	0.9 ^b ; 1.8 (2.2; 1.9)	
CH ₃ CH ₂ OH + CH ₄ → CH ₃ CH ₃ + CH ₃ OH	4.9 ^b ; 3.7 (5.9)	
CH ₃ OCH ₃ + H ₂ O → 2CH ₃ OH	2.3 ^b (5.9; 5.3)	
CH ₂ (OH) ₂ + CH ₄ → 2CH ₃ OH	14.3 ^b ; 14.0 (15.4) ^c	
CH ₃ OOH + H ₂ O → CH ₃ OH + HOOH	3.3 (8.1) ^c	
HOOOH + H ₂ O → 2HOOH	9.3	
Homodesmotic Reactions		
1 + 5C ₂ H ₆ → 5CH ₃ CH ₂ CH ₃	-6.2 ^b (-4.4; -6.7)	6.3
2 + 3C ₂ H ₆ + 2CH ₃ OH → 2CH ₃ CH ₂ CH ₃ + 2CH ₃ CH ₂ OH + CH ₃ OCH ₃	-5.8 ^b (-5.3)	5.9
3 + C ₂ H ₆ + 4CH ₃ OH → 2CH ₃ CH ₂ OH + 2CH ₃ OCH ₃ + CH ₂ (OH) ₂	-9.7 ^b (-10.7)	6.0
4 + 2C ₂ H ₆ + 2CH ₃ OH + H ₂ O ₂ → CH ₃ CH ₂ CH ₃ + 2CH ₃ CH ₂ OH + 2CH ₃ OOH	-6.3	
5 + 4CH ₃ OH + H ₂ O ₂ → CH ₃ OCH ₃ + 2CH ₂ (OH) ₂ + 2CH ₃ OOH	-15.0	
6 + C ₂ H ₆ + 2CH ₃ OH + 2H ₂ O ₂ → 2CH ₃ CH ₂ OH + 2CH ₃ OOH + HOOOH	-12.8	
7 + 2CH ₃ OH + 3H ₂ O ₂ → CH ₂ (OH) ₂ + 2CH ₃ OOH + 2HOOOH	-28.8	
8 + 5H ₂ O ₂ → 5HOOOH	-48.3	

a. Energies in kcal/mol. Numbers in parentheses correspond to experimental values, the first to reaction energies measured at 298 °K, the second, if available, to values at 0 °K corrected for zero-point energies.

b. Evaluated for standard geometries of two- and three-heavy atom systems.

c. Thermochemical estimates.

d. Upper half of Table — BSE values of the ideal unstrained ring; lower half of Table — thermochemical strain energies from Ref. 46a.

Table 10. Absolute Energies (hartree) of Three-heavy Atom Reference Molecules Obtained with Basis C

Molecule	Geometry		Ref.
	Standard	Optimized	
CH ₃ CH ₂ CH ₃	-118.26194	-118.26342	a, b
CH ₃ CH ₂ OH	-154.07433		a
CH ₃ OCH ₃	-154.06155		a
CH ₂ (OH) ₂	-189.89553	-189.89679	a, c
CH ₃ OOH	-189.78391	-189.79426	a, c
HOOOH	-225.51055	-225.53362	17

a. D. Cremer, *J. Comp. Chem.*, **3**, 154, 165 (1982).

b. J. S. Binkley, J. A. Pople and W. J. Hehre, *Chem. Phys. Lett.*, **36**, 1 (1975).

c. Partial optimization has been carried out with basis B.

between heavy atom bonds.⁴³ They are zero if the bond additivity hypothesis is fulfilled but become positive when the interactions between adjacent bonds lead to electronic stabilization. The theoretical BSE's of compounds 1-8 (Table 9) are positive or slightly negative. Experimental BSE's for 1, 2 and 3 indicate that the HF/C values are probably somewhat too small, even if vibrational corrections are taken into account (Table 9, compound 1). This is in line with the observation that

puckering of the rings is slightly underestimated by the theory. A somewhat higher *q* value would imply larger dihedral angles and an increase in bond-bond interactions, thus leading to more positive BSE values.

The largest BSE's are found for 3 and 5. Both molecules contain the O-C-O frame of CH₂(OH)₂. The BSE of CH₂(OH)₂ is relatively large (14 kcal/mol, Tables 9 and 10), which is due to strong anomeric interactions between the C-O bonds. They are fully developed if both OCOH units adopt a synclinal conformation leading to a C₂-symmetrical form of the molecule (one O-H bond above, one below the three-heavy atom plane).⁴⁴ A similar arrangement of C-O bonds is only possible in the T forms of 3 and 5. Delocalization of the oxygen lone pairs in the adjacent C-O bond causes a stabilization of the T forms.⁴ Similar but weaker interactions are present in the other oxolanes as revealed by the BSE's of the appropriate three-heavy atom molecules also listed in Table 9.

In each oxolane there are five bond-bond interactions. Summed over the BSE's of the corresponding five reference compounds, the BSE of an ideal unstrained oxolane results (last column of Table 9). These hypothetical BSE's are considerably larger than the actual BSE's thus indicating that compounds 1-8 are more or less destabilized by ring strain. We define the strain energy (SE) of an oxolane as the difference between the ideal and the actual BSE. This definition is equivalent to setting the SE of a ring molecule equal to the negative group separation

energy (GSE) of its homodesmotic reaction* as was first suggested by George, Trachtman, Bock, and Brett.⁴⁵ Homodesmotic reactions for 1–8 and the corresponding GSE's are also given in Table 9.

Theoretical and experimental GSE's of compounds 1, 2 and 3 are in better agreement than the corresponding BSE's (Table 9). Also the conventional strain energies (CSE) of 1, 2 and 3 (6.3, 5.9, and 6.9 kcal/mol) evaluated from thermochemical data with the aid of the group increment method,⁴⁶ are close to the *ab initio* SE's. This lends support to the idea of discussing the ring strain of 1–8 in terms of the computed GSE values.

The SE's of 1 and 2 are about 6 kcal/mol. Incorporation of an O–O bond in the five membered ring does not increase ring strain, mainly because of the mode of puckering, which lowers destabilizing electronic effects (see above). This is similar to the situation in cyclopentene where, in spite of the double bond, a relatively low SE of 5.9 kcal/mol has been found.^{46a}

There is a significant increase of the SE if the five-membered ring contains three or more O atoms. For the two ozonides 5 and 6, SE's of 15 and 13 kcal/mol are obtained, which are significantly larger than the 6 kcal/mol assumed in previous studies of these molecules.⁴⁷ Separate calculations published elsewhere show that the SE's in Table 9 lead to heats of formation of 5 and 6 which are in fair agreement with independently obtained estimates.^{7b,41}

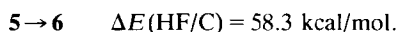
The computed SE's of 7 and 8 (29 and 48 kcal/mol) are larger than the O–O bond dissociation energies predicted for alicyclic polyoxides.⁴⁸ This means that 7 and 8 are unstable species. If they are formed, e.g. by a symmetry-allowed [π 4, + π 2,]-cycloaddition between O₃ and H₂CO or O₃ and 'O₂, immediate rupture of an O–O bond will lead to decomposition products. In the case of the ozonide 6, an O–O bond dissociation energy of 17 kcal/mol may be predicted if the corresponding value for alicyclic trioxides is assumed to be close to 30 kcal/mol. Similarly for 4 a value of 32 kcal/mol results using a reference energy of 38 kcal/mol.⁴⁸

It should be noted that the SE's of Table 9 are not very useful when discussing the puckering of the oxolanes. In order to establish a relationship between *q* and ring strain, the SE's of the planar forms (SEP) have to be evaluated. SEP values are listed in the last column of Table 6. They reveal that the dependence of the calculated puckering amplitude on the number of O–O bonds or ether bridges is actually a result of increased or decreased strain in the planar forms. This is illustrated in Fig. 6 where *q* values are plotted as a function of the computed SEP's. The resulting curve consists of two branches, the first showing the decrease of *q* (relative to *q*(1)) with the number of ether bridges, the second showing the increase of *q* with the number of O–O bonds.

Finally, it is useful to estimate average O–O bond energies from the formal isomerization reactions



and



These isomerizations are characterized by the conversion of two C–O bonds into a C–C and an O–O single bond. If the C–C and the C–O bond energies are taken to be about 80 kcal/mol,⁴⁹ then average O–O bond energies of 23 and 22 kcal/mol are obtained from the isomerization energies. These values may be corrected for strain and

bond–bond interaction effects utilizing the BSE's of 3–6 (Table 9). In this way an average O–O bond energy of 34 kcal/mol for unstrained alicyclic peroxides results which is identical with the value obtained from thermochemical measurements on peroxides.⁴⁹

CONCLUSIONS

The *ab initio* investigation presented here has led to a new procedure for analyzing structure, conformation and stability of five-membered ring compounds. It comprises the following steps: (1) Calculation of the energy of the planar form. (2) Determination of BSE and SEP. (3) Choice of the conformational model to be used for puckered ring forms; a large BSE value for the strainfree ring is indicative of strong bond–bond interactions and suggests that a flexible pseudorotor model (Table 1) has to be used. (4) Analysis of the HOMO's of the planar ring; the puckering mode is selected which should lead to largest stabilization of π -type HOMO's (see Table 7 and Fig. 5). (5) Theoretical energies are calculated at suitable points in *q*, ϕ -space. The potential *V* is determined with the aid of Eq. (1). (6) Location and energies of the stationary points of *V* are analyzed using calculated orbital energies, BSE and SE values. (7) Substituent effects are estimated on the basis of substituent orientation and π -type overlap.

The usefulness of this procedure has been demonstrated for the oxolanes 2–8. Other applications, e.g. to azolidines, oxazolidines, thiazolidines, thiolanes, etc. should be straightforward.

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REFERENCES AND NOTES

- For reviews see a. B. Fuchs in E. L. Eliel and N. L. Allinger, eds., *Topics in Stereochemistry*, Vol. 10, Wiley-Interscience, New York, 1977, p. 1; b. J. Laane in J. R. Durig, ed., *Vibrational Spectra and Structure*, Vol. 1, Marcel Dekker, New York, 1982; c. C. Romers, C. Altona, H. R. Buys and E. Havinga in E. L. Eliel and N. L. Allinger, eds., *Topics in Stereochemistry*, Vol. 4, Wiley-Interscience, New York, 1969; d. A. C. Legon, *Chem. Rev.*, **80**, 231 (1980).
- a. J. E. Kilpatrick, K. S. Pitzer and R. Spitzer, *J. Am. Chem. Soc.*, **80**, 6697 (1958); b. K. S. Pitzer and W. E. Donath, *J. Am. Chem. Soc.*, **81**, 3213 (1959).
- D. Cremer and J. A. Pople, *J. Am. Chem. Soc.*, **97**, 1358 (1975).
- D. Cremer, *J. Chem. Phys.*, **70**, 1898 (1979).
- N. I. Krinsky in H. H. Wasserman and R. W. Murray, eds., *Singlet Oxygen*, Academic Press, New York, 1979, p. 597.
- P. S. Bailey, *Ozonation in Organic Chemistry*, Vol. 1, Academic Press, New York, 1978.
- a. D. Cremer, *J. Am. Chem. Soc.*, **103**, 3619 (1981); b. *J. Am. Chem. Soc.*, **103**, 3627 (1981); c. *J. Am. Chem. Soc.*, **103**, 3633 (1981).
- G. Klopman and C. M. Joiner, *J. Am. Chem. Soc.*, **97**, 5287 (1975).
- L. Radom and J. A. Pople, *J. Am. Chem. Soc.*, **92**, 4786 (1970).
- A. Veillard in W. J. Orville-Thomas, ed., *Internal Rotation in Molecules*, Wiley, New York, 1974, p. 385.

* Homodesmotic reactions form a subclass of isodesmic reactions. An *isodesmic* reaction in which there are equal numbers of each type of atom (characterized by its hybridization and the number of H atoms attached to it) in reactants and products is called a *homodesmotic* reaction.

11. D. Cremer and J. A. Pople, *J. Am. Chem. Soc.*, **97**, 1354 (1975).
12. D. Cremer, *Isr. J. Chem.*, **20**, 12 (1980).
13. a. D. Cremer, *J. Chem. Phys.*, **70**, 1911 (1979); b. *J. Chem. Phys.*, **70**, 1928 (1979).
14. D. Cremer, *J. Am. Chem. Soc.*, **99**, 1307 (1977).
15. D. Cremer, O. V. Dorofeeva and V. S. Mastryukov, *J. Mol. Struct.*, **75**, 225 (1981).
16. D. Cremer, *J. Chem. Phys.*, **69**, 4440 (1978).
17. D. Cremer, *J. Chem. Phys.*, **69**, 4456 (1978).
18. D. Cremer and D. Christen, *J. Mol. Spectrosc.*, **74**, 480 (1979).
19. W. J. Hehre, R. F. Stewart and J. A. Pople, *J. Chem. Phys.*, **51**, 2657 (1969).
20. R. Ditchfield, W. J. Hehre and J. A. Pople, *J. Chem. Phys.*, **54**, 724 (1971).
21. J. A. Pople and M. S. Gordon, *J. Am. Chem. Soc.*, **89**, 4253 (1967).
22. P. C. Hariharan and J. A. Pople, *Theor. Chim. Acta*, **28**, 213 (1973).
23. L. A. Carreira, G. J. Jiang, W. B. Person and J. N. Willis, Jr., *J. Chem. Phys.*, **56**, 1440 (1972).
24. a. W. J. Adams, J. H. Geise and L. S. Bartell, *J. Am. Chem. Soc.*, **92**, 5013 (1970); b. R. Poupko, Z. Luz and H. Zimmermann, *J. Am. Chem. Soc.*, **104**, 5307 (1982).
25. H. J. Geise, W. J. Adams and L. S. Bartell, *Tetrahedron*, **25**, 3045 (1969).
26. a. G. G. Engerholm, A. C. Luntz, W. D. Gwinn and D. O. Harris, *J. Chem. Phys.*, **50**, 2446 (1969); b. J. A. Greenhouse and H. L. Strauss, *J. Chem. Phys.*, **50**, 124 (1969).
27. a. J. R. Durig and D. W. Wertz, *J. Chem. Phys.*, **49**, 675 (1968); b. J. A. Greenhouse and H. L. Strauss, *J. Chem. Phys.*, **50**, 124 (1969).
28. P. A. Baron and D. O. Harris, *J. Mol. Spectrosc.*, **49**, 70 (1974).
29. a. P. Rademacher and W. Elling, *Liebigs. Ann. Chem.*, 1473 (1979); b. D. J. Coughlin, R. S. Brown and R. G. Salomon, *J. Am. Chem. Soc.*, **101**, 1533 (1979); c. T. Kondo, M. Tanimoto and M. Matsumoto, *Tetrahedron Lett.*, **21**, 1649 (1980).
30. a. C. W. Gillies and R. L. Kuczkowski, *J. Am. Chem. Soc.*, **94**, 6336 (1972); b. R. L. Kuczkowski, C. W. Gillies and K. L. Gallaher, *J. Mol. Spectrosc.*, **60**, 361 (1976); c. U. Mazur and R. L. Kuczkowski, *J. Mol. Spectrosc.*, **65**, 84 (1977).
31. C. K. Kohmiller and L. Andrews, *J. Am. Chem. Soc.*, **103**, 2578 (1981) and private communication.
32. D. Cremer, unpublished results.
33. O. Kennard and D. G. Watson, *Molecular Structures and Dimensions*, Vols. 1-13, NVA Oosthoek, Utrecht, 1970-1982.
34. W. L. Duax and D. A. Norton, eds., *Atlas of Steroid Structure*, Vol. 1, Plenum, New York, 1975.
35. C. Altona and M. Sundaralingam, *J. Am. Chem. Soc.*, **94**, 8205 (1972).
36. C. Altona, H. R. Buys and E. Havinga, *Recl. Trav. Chim. Pays-Bas*, **85**, 973 (1966).
37. J. D. Dunitz, *Tetrahedron*, **28**, 5459 (1972).
38. G. M. Badger, *Aromatic Character and Aromaticity*, Cambridge University Press, New York, 1969.
39. M. J. S. Dewar and G. J. Gleicher, *J. Am. Chem. Soc.*, **87**, 692 (1965).
40. L. G. Harruff, M. Brown and V. Boekelheide, *J. Am. Chem. Soc.*, **100**, 2893 (1978).
41. D. Cremer, unpublished results.
42. D. Cremer, J. S. Binkley and J. A. Pople, *J. Am. Chem. Soc.*, **98**, 6836 (1976).
43. W. J. Hehre, R. Ditchfield, L. Radom and J. A. Pople, *J. Am. Chem. Soc.*, **92**, 4796 (1970).
44. G. A. Jeffrey, J. A. Pople and L. Radom, *Carbohydr. Res.*, **25**, 117 (1972).
45. a. P. George, M. Trachtman, C. W. Bock and A. M. Brett, *Tetrahedron*, **32**, 317 (1976); b. J. D. Dill, A. Greenberg and J. F. Liebman, *J. Am. Chem. Soc.*, **101**, 6814 (1979).
46. a. S. W. Benson, *Thermochemical Kinetics*, 2nd ed., Wiley, New York, 1972; b. K. Pihlaja, *Acta Chem. Scand., Ser B*, **25**, 451 (1971).
47. a. W. R. Wadt and W. A. Goddard, *J. Am. Chem. Soc.*, **97**, 3004 (1975); b. L. B. Harding and W. A. Goddard, *J. Am. Chem. Soc.*, **100**, 7180 (1978).
48. P. S. Nangia and S. W. Benson, *J. Phys. Chem.*, **83**, 1138 (1979).
49. G. J. Janz, *Thermodynamic Properties of Organic Compounds*, Academic Press, New York, 1967.