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SELF-ASSEMBLY OF FRAME STRUCTURES.
10.[†] STEREOCHEMISTRY OF 2,5-DIOXABICYCLO[2.2.1]HEPTANE-3,6-DIONE

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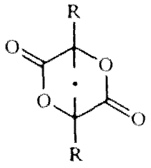
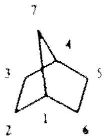
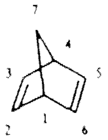
By optimization of the geometry of 2,5-dioxabicyclo[2.2.1]heptane-3,6-dione (I) with an ab initio *(RHF/6-31G*) calculation, we have found that a single synchro(+, +)-twist form (A) corresponds to the* (1R,4R)-*enantiomer (the dihedral angles of the lactone bridges are φ_0 = 2.6°). According to MM2(91) and MM3(92) calculations,* (1R,4R)-*I exists as the synchro(+, +)-A-twist (φ_0 = 3.9°) and the synchro(−, −)-B-twist (φ = −3.8°) forms, respectively. Investigating the torsional energy surface of the dilactone I (MM2(91)), we found only the* (1R,4R,P)-*diastereomeric form (A), which is stabilized compared with the* (1R,4P,M) *form (B) (probably as a result of the more preferred dipole–dipole interaction of the carbonyl groups). According to the calculated puckering coordinates, the five-membered and six-membered moieties of the bicycle I are flattened compared with norbornane.*

This work is part of a systematic investigation of the stereochemistry of bridged dilactones (see [2]).

The stereochemical principles of synthesis [3-5] and origins of optical activity [6] of [2.2.1]bicyclodilactones of C_2 symmetry are currently under intense study. Nevertheless, no structural data are available on dilactones of this type, although the structure of related compounds is well known: γ- and δ-lactones [7-11], norbornane (IV) [12-18], norbornadiene (V) [14, 17], and the dilactones VI, VII [2].


I R = H; II R = Me;
III R = *t*-Bu


IV (C_{2v})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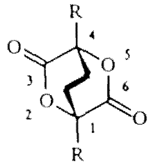
VI R = H; VII R = Me;

For dilactones of series I, we may expect either stabilization of the [2.2.1] bicyclic skeleton as the eclipsed form (similar to norbornane IV), enhanced by ester resonance (similar to norbornadiene V), or the twist form, due to electrostatic interaction of the dipoles of the ester groups (similar to dilactones VI, VII).

The main goal of this work was to establish the conformation of the dilactone I in the free state.

[†] For Communication 9, see [1].

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TABLE 1. Bond Lengths and Bond Angles in Molecule I

Parameter	RHF/6-31G*	MM2(91)	MM3(92)
	Bond length (d, Å)^a		
$C_{(1)}-O_{(2)}$	1,432	1,425	1,467
$O_{(2)}-C_{(3)}$	1,349	1,364	1,377
$C_{(3)}-C_{(4)}$	1,525	1,527	1,509
$C_{(1)}-C_{(7)}$	1,529	1,524	1,525
$C_{(3)}-O_{(8)}$	1,173	1,203	1,213
	Bond angles (ω, degrees)		
$C_{(1)}O_{(2)}C_{(3)}$	107,6	105,3	106,0
$O_{(2)}C_{(3)}C_{(4)}$	104,3	104,5	106,1
$O_{(2)}C_{(3)}O_{(8)}$	124,8	126,8	124,3
$C_{(4)}C_{(3)}O_{(8)}$	130,9	128,7	129,5
$\Sigma\ \omega_{exo}{}^b$	255,7	255,5	253,8
$\Delta\ \omega_{exo}{}^b$	6,1	1,9	5,2
$O_{(2)}C_{(1)}C_{(6)}$	105,1	108,3	104,0
$O_{(2)}C_{(1)}C_{(7)}$	102,4	104,0	100,5
$C_{(6)}C_{(1)}C_{(7)}$	99,4	98,8	100,1
$C_{(1)}C_{(7)}C_{(4)}$	90,0	88,4	92,6
$H_{(12)}C_{(7)}H_{(13)}$	110,9	110,5	110,0

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a) r_e-type (*ab initio*) and r_g-type (MM2,MM3). b) The sum (Σ) and the difference (Δ) of the exocyclic bond angles at the C=O bond.

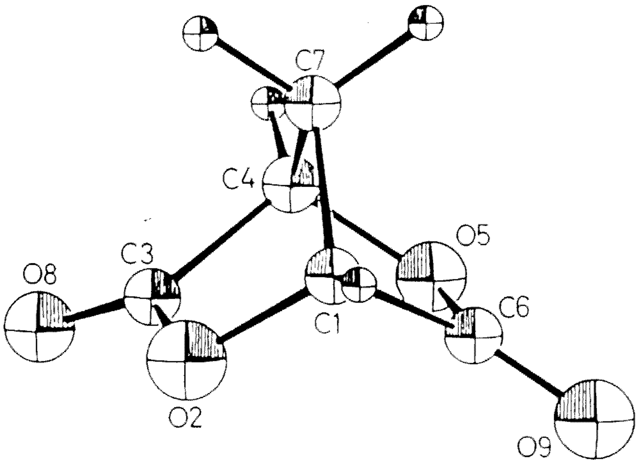

Fig. 1. Geometry of molecule I (MM2)(91).

Attempts to obtain the simplest dilactone I [4], in contrast to dilactones II [3] and III [4], proved to be unsuccessful. So we studied the structure of molecule I (specifically, the (1*R*,4*R*)-enantiomer) by *ab initio* and molecular mechanics (MM) theoretical methods. The *ab initio* calculations for homologs of the dilactone I in extended basis sets are limited by the size of the molecules. Therefore we used the molecular mechanics method [2, 9-12], which sufficiently adequately reproduces the geometry of γ-, δ-lactones and bicycles IV, VI, and VII.

Full optimization of the geometry of dilactone I by the *ab initio* method was done at the RHF level in the 6-31G* basis set using the program Gaussian 92 [19] with restriction of the symmetry of molecule I to the point group C_2. The geometry and energy of the structure of dilactone I were calculated by the molecular mechanics method without restriction of the symmetry using the programs MM2(91) [20] and MM3(92) [11] (improved versions, respectively, of MM2(77) [21] and MM3(89) [22] force fields).

The results of optimization of the geometry of dilactone I by *ab initio* and molecular mechanics methods are presented in Fig. 1 and in Tables 1 and 2, along with the energies and dipole moments of the calculated structures for I (Table 2).

According to the values of the dihedral angles of the lactone bridges $C_{(1)}O_{(2)}C_{(3)}C_{(4)}$ and $C_{(4)}C_{(5)}C_{(6)}C_{(1)}$ (Table 2), the five-membered and six-membered moieties in molecule I are characterized by slightly twisted envelope and boat forms.

TABLE 2. Principal Dihedral Angles (τ, φ, degrees), Dipole Moments (μ, debyes), Puckering Coordinates of Five-Membered (P, τ_m) and Six-Membered (ψ_2, θ, S) Moieties[a] and Calculated Energies[b] of Dilactone I

Parameter	RHF/6-31G*	MM2(91)	MM3(92)
$C_{(1)}O_{(2)}C_{(3)}C_{(4)}$ (τ_0, φ_1)	2,6	3,9	-3,8
$O_{(2)}C_{(3)}C_{(4)}C_{(7)}$ (τ_1)	-38,4	-40,7	-32,0
$C_{(3)}C_{(4)}C_{(7)}C_{(1)}$ (τ_2)	53,8	55,2	51,6
$C_{(4)}C_{(7)}C_{(1)}O_{(2)}$ (τ_3)	-54,1	-56,3	-54,8
$C_{(7)}C_{(1)}O_{(2)}C_{(3)}$ (τ_4)	34,5	34,9	38,4
$O_{(2)}C_{(3)}C_{(4)}O_{(5)}$ (φ_2)	67,3	67,3	71,6
$C_{(3)}C_{(4)}O_{(5)}C_{(6)}$ (φ_3)	-68,9	-69,5	-64,9
$C_{(1)}O_{(2)}C_{(3)}O_{(8)}$	-176,9	-176,8	178,3
μ, D	5,36	3,64	4,76
P, degrees	16,0	15,3	22,2
τ_m, degrees	56,0	57,2	55,8
ψ'_2, degrees	271,7	272,5	266,6
θ, degrees	89,8	89,6	89,7
S	1,120	1,125	1,123
σ, degrees[d]	0,5	0,9	0,7

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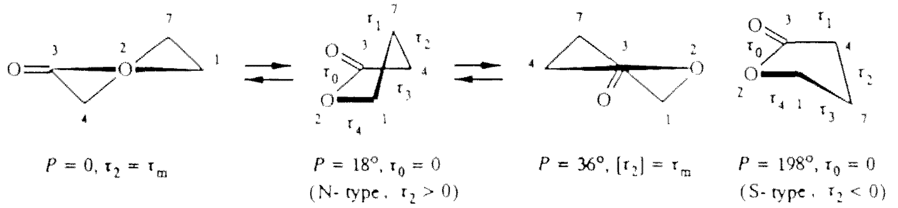
a) P and ψ are the phase angles of pseudorotation, θ is the polar angle, τ_m and S are the puckering amplitudes for the rings. b) Calculated energies: −491.11557 hartrees (*ab initio*), 32.91 (MM2), 54.51 (MM3) kcal/mole. c) Due to the C_2 symmetry of the molecules, the angles are $\varphi_1 = \varphi_{1'}$, $\varphi_2 = \varphi_{2'}$, $\varphi_3 = \varphi_{3'}$. d) The acceptable error (σ) should be less than 3-5° [24].



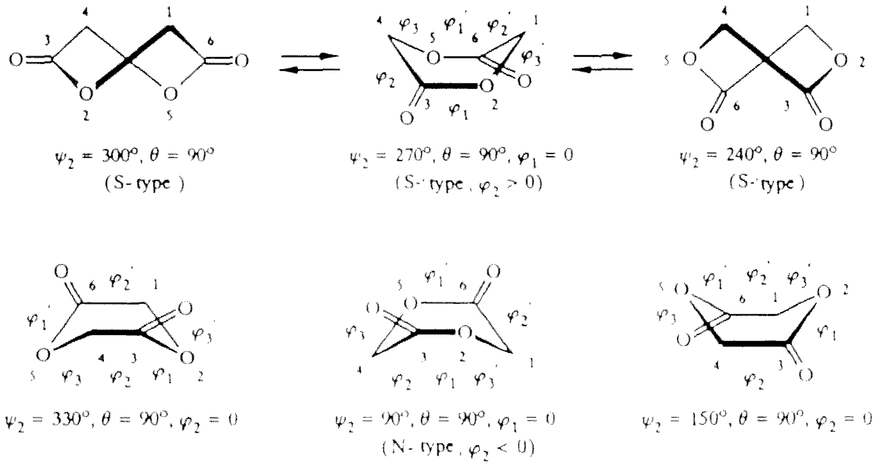
$P = 0$, $\tau_2 = \tau_m$

$P = 18°$, $\tau_0 = 0$ (N-type, $\tau_2 > 0$)

$P = 36°$, $|\tau_2| = \tau_m$

$P = 198°$, $\tau_0 = 0$ (S-type, $\tau_2 < 0$)

(a) Ring 1(2)



$\psi_2 = 300°$, $\theta = 90°$ (S-type)

$\psi'_2 = 270°$, $\theta = 90°$, $\varphi_1 = 0$ (S-type, $\varphi_2 > 0$)

$\psi'_2 = 240°$, $\theta = 90°$ (S-type)

$\psi_2 = 330°$, $\theta = 90°$, $\varphi_2 = 0$

$\psi_2 = 90°$, $\theta = 90°$, $\varphi_1 = 0$ (N-type, $\varphi_2 < 0$)

$\psi_2 = 150°$, $\theta = 90°$, $\varphi_2 = 0$

b Ring

Fig. 2. Selected canonical envelope and half-chair forms for the γ-butyrolactone moiety (ring 1 (2)), the boat and twist form of the δ-dilactone moiety (ring 3) of dilactone I, and also the phase angles (P,ψ_2) and the polar angle (θ) for these rings.

According to the *ab initio* and MM2(91) data, the bicyclic skeleton of dilactone I has the synchro(+,+)-twist form (A), in contrast to the MM3(92) calculations which the synchro(−,−)-twist form (B).

For a quantitative description of the calculated models of molecule I, we determined the puckering coordinates of the five-membered (P, τ_m) and six-membered (ψ_2, θ, S) moieties (Table 2) based on the endocyclic torsional angles τ and φ (Table 2, Fig. 2) using the Altona [23] and Zefirov–Palyulin [24] methods respectively. These data are necessary for comparison of the stereochemistry of the structures obtained for the dilactone I both with each other and with the known structures of the bicycles IV and VI, the γ-butyrolactone VIII, and the cyclopentane IX.*

The phase angle of pseudorotation P and the puckering amplitude τ_m characterize respectively the shape and degree of pucker for the γ-lactone rings of the dilactone I [23]. For the δ-dilactone monocycle of molecule I, the corresponding parameters are the phase angle (ψ_2), the polar angle (θ), and the total amplitude S [24].

In accordance with the previously proposed [6] conformational analysis of γ-lactones and the numbering of the system shown in Tables 2 and in Fig. 2, the "ideal" enantiomeric envelope forms of the γ-lactone ring have phase angles $P = 18°$ and 198° ($\tau_0 = 0$), respectively.

We considered the shape of the γ-lactone ring [6] as either N-type ($\tau_2 > 0$, $P_N = 0(360) \pm 90°$) or the enantiomeric S-type ($\tau_2 < 0$, $P_S = 180 \pm 90°$). Analogously, the "ideal" enantiomeric boat forms of the δ-dilactone ring have phase angles $\psi_2 = 90°$ or 270° and polar angle $\theta = 90°$ ($\varphi_1 = \varphi_{1'} = 0$) (Fig. 2) [2]. The shape of the δ-dilactone ring is determined as S-type ($150° < \psi_2 < 330°$, $\theta = 90°$, $\psi_2 = \psi_{2'} > 0$) or the enantiomeric N-type ($\psi_2 < 150°$ or $\psi_2 > 330°$, $\theta = 90°$, $\varphi_2 = \varphi_{2'} < 0$) (Fig. 2).

When the phase angles P or ψ_2 deviate from the ideal values of 18° and 198° (P) or 90° and 270° (ψ_2), additional chirality of the five-membered or six-membered rings arises, independently of any substitution [25]. Therefore the twist forms of the γ-lactone ring with $P < 18°$, $P > 270°$ (N-type) and $198° < P < 270°$ (S-type) are denoted as "P" (plus) ($\tau_0 > 0$), and the twist forms with $18° < P < 90°$ (N-type) and $90° < P < 198°$ (S-type) are denoted as "M" (minus) ($\tau_0 < 0$), in accordance with IUPAC rules [25]. Analogously, the twist forms of the δ-dilactone ring with $\psi_2 < 90°$, $\psi_2 > 330°$ (N-type) and $270° < \psi_2 < 330°$ (S-type) are denoted [2] as "P" (plus) ($\varphi_1 = \varphi_{1'} > 0$), and the twist forms with $90° < \psi_2 < 150°$ (N-type) and $150° < \psi_2 < 270°$ (S-type) are denoted as "M" (minus) ($\varphi_1 = \varphi_{1'} < 0$).

Thus, according to the value of the phase angle P (Table 2), the identical (due to the C_2 symmetry) five-membered moieties (rings 1 and 2, Fig. 2) of the enantiomeric N-type ($\tau_2 > 0$, Table 2) in dilactone I are close in shape to the regular envelope of γ-butyrolactone and are slightly twisted toward the half-chair shape with $P = 0$ (*ab initio* and MM2 models) or toward the half-chair form with $P = 36°$ (Fig. 2) (MM3 structure).

Accordingly, the δ-dilactone moiety (ring 3, Fig. 2) of the enantiomeric S-type ($\varphi_2 > 0$), according to the value of the phase angle ψ_2 (Table 2), has the shape of an almost regular boat ($\varphi_2 = 270°$, $\theta = 90°$, Fig. 2) and is twisted toward the twist form with $\psi_2 = 300°$ according to the *ab initio* and MM2 calculations, or toward the twist form with $\psi_2 = 240°$ (Fig. 2) according to the MM3 model (Table 2). According to the value of the polar angle $\theta \sim 90°$ (Table 2), ring 3 in dilactone I is twisted according to a pseudorotation mechanism and not an inversion mechanism; i.e., it may have the boat or twist form but not the chair, half-chair, or half-boat form [24].

The nature of the change in the values of the phase angles $P > 18°$, $\psi_2 > 270°$ (*ab initio* and MM2) and $P < 18°$, $\psi_2 < 270°$ (MM3) corresponds to the above definition of degree of twist of the rings 1-3 as "P" (synchro(+,+)) and "M" (synchro(−,−)) respectively and is supported by analysis of the signs of the torsional angles of the lactone bridges (τ_0 and φ_1, Table 2).

Comparison of the MM2 structures for γ-butyrolactone VIII (Table 3, $P = 12.8°$, $\tau_m = 29.7°$) and dilactone I (Table 2) shows that including the γ-lactone ring in the rigid [2.2.1] structure of bicycle I stabilizes the five-membered ring 1 in a form closer to a regular envelope and strongly increases its degree of pucker; and the increase in degree of pucker of the γ-lactone ring in dilactone I, compared with the monocycle VIII, is greater than the increase in degree of pucker of the cyclopentane moiety in norbornane (Table 4) compared with the corresponding calculated structures for unsubstituted cyclopentane in the envelope form (C_S, $\tau_0 = 0$, $P = 18°$) ($\tau_1 = 24.2°$, $\tau_2 = 39.4°$, $\tau_m = 41.6°$ (4-31G); 25.1°, 40.5°, 42.6° (MM2); 24.2°, 39.2°, 41.2° (MM3) [12] (for the numbering of τ, see Table 4). However, on the whole, the degree of pucker for the γ-lactone moieties in the calculated structures for dilactone I (Table 2) is less than for the cyclopentane moieties in the

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*We calculated the puckering coordinates for compounds IV and VIII (Tables 3 and 4) and IX based on the values of their dihedral angles by the methods in [23, 24].

TABLE 3. Comparison of Structures for g-Butyrolactone VIII[a]

Parameter	*ab initio* [8][b,c]	MM2 [9][d]	MM3 [11]
$C(sp^2)-C(sp^3)$	—	1,514	—
$C(sp^2)-O$	1,335	1,359	—
$C=O$	1,180	1,211	—
$O-C(sp^3)$	1,419	1,421	—
$C-C(sp^2)-O$	110,5	108,9	110,1
$C(sp^2)-O-C$	112,1	111,2	110,3
$O-C=O$	123,0	—	123,0
$C-C=O$	127,8	—	126,9
$\Sigma\omega_{exo}$ [e]	250,8	—	249,9
$\Delta\omega_{exo}$ [e]	4,8	—	3,9
μ, D [f]	5,02	3,75	4,23

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a) Bond lengths in Å (see (a), Table 1), bond angles in degrees. b) Optimization of the geometry (RHF/6-31G*). c) $\varphi(C-O-C{=}O) = -177.2°$, $\tau_0 = 2.4°$. d) $\tau_0 = 3.2°$, $\tau_1 = -21.2°$, $\tau_2 = 29.0°$, $\tau_3 = -28.3°$, $\tau_4 = 16.4°$ (for numbering, see Fig. 2), $P = 12.8°$, $\tau_m = 29.7$. d) See (b) in Table 1. e) Dipole moment in debyes.

TABLE 4. Torsional Angles (t, j) and Puckering Coordinates[a] for Norbornane IV

Parameter [b,c]	GED [13]	4-21G [16]	MM2 [12]	MM3 [12]
$C_{(1)}C_{(2)}C_{(3)}C_{(4)}$ (τ_0)	0	0	0	0
$C_{(2)}C_{(3)}C_{(4)}C_{(7)}$ (τ_1)	-35,8	-35,1	-36,2	-34,9
$C_{(3)}C_{(4)}C_{(7)}C_{(1)}$ (τ_2)	56,3	55,7	56,5	55,5
$C_{(2)}C_{(3)}C_{(4)}C_{(5)}$ (φ_2)	71,6	71,3	71,4	71,0
τ_m, degrees [d]	59,2	58,6	59,4	58,4
S[d]	1,170	1,166	1,167	1,161

a) Due to the C_{2v} symmetry of the molecule, the phase angles ($P = 18°$; $\psi_2 = 270°$) and the polar angle ($\theta = 90°$) are identical for all the structures. b) The numbering of the torsional angles is as in dilactone I (Fig. 2). c) $\tau_0 = \varphi_1$, $\tau_1 = \tau_4$, $\varphi_2 = \varphi_3$. d) Puckering amplitudes.

structures for norbornane IV (Table 4), optimized by the appropriate methods. This is accompanied by shortening of the $C_{(1)}C_{(7)}$ bond and a decrease in the $C_{(1)}-C_{(7)}-C_{(4)}$ bond angle in molecule I (Table 1) compared with the structure for norbornane I according to data from optimization by apropriate methods (1.539 Å and 94.4° (RHF/6-31G*) [18]; 1.538 Å and 92.5° (MM2) [12]; 1.540 Å and 95.0° (MM3) [12]). It is interesting that in the structure of norbornadiene V, in contrast to the dilactone I, the degree of pucker of the five-membered moieties is increased compared with norbornane IV, which is accompanied by a lengthening of the $C_{(1)}-C_{(7)}$ bond (1.573 Å, gas-phase electron diffraction (GED) [14]) and an increase in the angle $C_{(1)}-C_{(7)}-C_{(4)}$ (94.1° (GED) [14]) in molecule V compared with the bicycle IV (1.546 Å and 93.4° (GED) [13]; 1.560 Å and 93.1° (GED) [14]).

These changes in the geometric parameters for the bridgehead carbon $C_{(7)}$ in bicycles I and V compared with molecule IV can be explained by the fact that the $C_{(1)}\ldots C_{(4)}$ distance in norbornadiene V is several hundredths of angstroms greater [14] than in norbornane IV (2.26 Å [14] and 2.317 Å [15] (GED), r_g type) while it is less in the dilactone I (2.126 Å (MM2), r_g type). At the same time, flattening of the d-dilactone ring in the structures for molecule I (according to the value of the total amplitude S, Table 2) compared with the cyclohexane ring in molecule IV (Table 4) is consistent with flattening of the six-membered moiety in the bicycle V ($F[C_{(1)}C_{(2)}C_{(3)}C_{4)}/C_{(4)}C_{(5)}C_{(6)}C_{(1)}] = 115.6°$ (GED) [14]; 114.1° (3-21G) [17]) compared with bicycle IV ($F = 113.1°$ (GED) [13, 14]; 112.1° (3-21G) [17]).

As expected, including the δ-dilactone ring (3) in the [2.2.1] bicyclic system of molecule I leads to a significant increase in the pucker and less twist for ring 3 (Table 2) compared with the analogous ring in the less rigid [2.2.2] bicyclic system of molecule VI ($\psi_2 = 273.8°$, $\theta = 89.8°$, $S = 0.934$, RHF/6-31G*) [2]. The increase in the $C_{(1)}\ldots C_{(4)}$ distance in dilactone VI

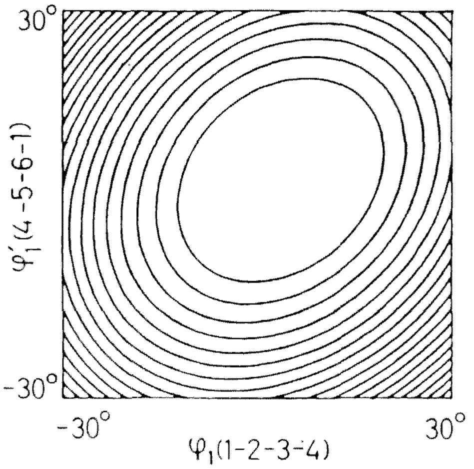


Fig. 3. Torsional energy surface of (1*R*,4*R*)-dilactone I (MM2(91)) (the contour separation is equal to 1 kcal/mole).

(2.462 Å, RHF/6-31G*) [2] compared with dilactone I (2.163 Å, RHF/6-31G*) corresponds to an increase in the analogous distance by ~0.3 Å in the bicyclo[2.2.2]octane or the bicyclo[2.2.2]octa-2,5-diene compared with the bicycles IV or V respectively [14].

From x-ray diffraction data [7] and calculations by the *ab initio* [8], MM2 [9, 10], and MM3 [11] methods, we know that the *E* form of the C−C(=O)−O−C lactone group of γ- and δ-lactones is characterized by coplanarity of this moiety and the following structural features: a) the C(sp^2)−O−C endocyclic angle is greater than the O−C(sp^2)−C angle; b) the O=C−C exocyclic angle is greater than the O=C−O angle (Table 3). As we see from Table 1, the geometry of the lactone moieties of the *ab initio* and MM2 structures of dilactone I completely correspond to these characteristics, in contrast to the MM3 model.

The rigid frame of molecule I is responsible for the appreciable decrease in the endocyclic bond angles at the carbonyl carbons $C_{(3)}$, $C_{(6)}$ and the ether oxygens $O_{(2)}$, $O_{(5)}$ (Table 1) compared with data for the corresponding calculated structures of γ-butyrolactone VIII (Table 3) and dilactone VI [2], which is accompanied by an increase in the sum ($\Sigma\omega_{exo}$) and the difference ($\Delta\omega_{exo}$) of the exocyclic angles at C=O in bicycle I (Table 1) compared with the corresponding data for compounds VIII (Table 3) and VI (249.4° and 3.4° (RHF/6-31G*)) [2]. Reduction of the value of $\Delta\omega_{exo}$ in the MM2 structure of dilactone I (Table 1) is a characteristic feature of the MM2 force field in the calculations for γ-lactones [26].

The increase in $\Sigma\omega_{exo}$ at the $C_{(3)}$, $C_{(6)}$ atoms and the decrease in $\Sigma\omega_{endo}$ at the $C_{(1)}$, $C_{(4)}$ atoms (Table 1) compared with the corresponding sums of the angles for the "ideal" sp^2- (240°) and sp^3-hybridized (332.4°, tertiary) carbons promotes a decrease in the 1,3-repulsions between the exo substituents and the atoms of the bicycle I [27] and the steric interaction of unshared electron pairs of the oxygen atoms in the *E* form of the lactone groups [8].

According to the familiar principles in [18], compression of the endocyclic angles at the $C_{(3)}$, $C_{(6)}$ atoms in molecule I should lead to enhancement of both the *p*-character of the hybrid orbitals of the carbonyl carbons $C_{(3)}$, $C_{(6)}$ in the endocyclic bonds (i.e., weakening of these bonds) and the *s* character of the hybrid orbitals of these carbons in the exocyclic bonds (i.e., strengthening of the latter). In fact, in the calculated structures for dilactone I, we observe lengthening of the O−C(sp^2) and C(sp^2)−C endocyclic bonds, and also shortening of the C=O exocyclic bonds (Table 1) compared with the corresponding models for g-butyrolactone VIII (Table 3).

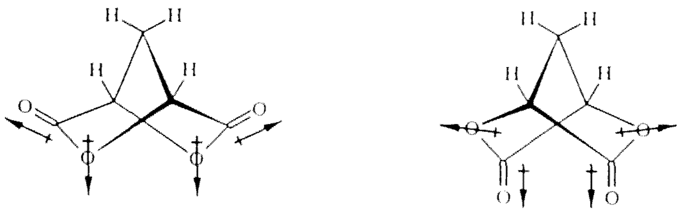
Direct comparison of the internuclear distances in the *ab initio* and MM models of molecule I (Table 1) is limited by the fact that the quantum chemical calculations give nonvibrational (equilibrium) values for the bond lengths (r_e type), while the MM method gives the average internuclear distances (r_g type) [12, 22]. However, the comparison of the torsional angles in these structures is sufficiently correct [7].

The above-noted lengthening of the formally single C−O bond in dilactone I is probably a consequence of the limitations due to the strained [2.2.1] bicyclic skeleton, which is supported by the very long $C_{(2)}-C_{(3)}$ bond in norbornane according to GED data [13], *ab initio* [16-18] and MM3 calculations [12]. The combined effect of lengthening of the C−O bonds and the degree of twist of the lactone bridges (Tables 1 and 2) should lead to some decrease in $n_0-\pi^*$ (C=O) conjugation. One of the consequences of this change is the observed shortening of the carbonyl bond in molecule I (Table 1). Thus, in the less rigid [2.2.2] bicyclic system of dilactone VI (RHF/6-31G*) [2], the appreciable increase in the endocyclic angle at the carbonyl carbons (110.6°) compared with dilactone I (Table 1) is accompanied by shortening of the ether bond O–C (1.336 Å) and lengthening of the carbonyl bond (1.178 Å), in accordance with the principles in [18].

As noted above, according to data from the *ab initio* and MM2 calculations (in contrast to MM3), the stable form of (1*R*,4*R*)-dilactone I is the synchro(+,+)-twist form (A). The reason for the stabilization of the diastereomeric (1*R*,4*R*,*P*)-form compared with the (1*R*,4*R*,*M*) form (B) may involve the following.

Obviously the conformation of the dilactone I may be determined mainly by steric and electrostatic interactions, and also the effect of $n_0-\pi^*$(C=O) conjugation. Comparison of both diastereomeric forms A and B of dilactone I shows that the relative stability of one of these twist forms cannot be explained on the basis of steric interactions or the effect of $n_0-\pi$(C=O) conjugation, in contrast to analysis of the intramolecular dipole–dipole interactions (DDI) (Scheme 1). Thus the *trans* orientation of the stronger dipoles of the C=O groups (μ = 2.75 D [28]) is more preferred in the A form than in the B form, and in the latter the *trans* orientation of the weaker dipoles of the C–O–C groups is preferred (μ = 1.29 D [28]). Therefore we may suppose that the dipole–dipole destabilization of the A form is less than for the B form. According to an investigation of the torsional energy surface of (1*R*,4*R*)-dilactone I using the program MM2(91) (Fig. 3), no conformer but the A form is found. This, together with the data for molecule I calculated by the *ab initio* method, allows us to say that dilactone I in the free state exists in the form of a single diastereomeric (1*R*,4*R*,*P*) twist form (A) of symmetry C_2.

Scheme 1



(1*R*, 4*R*, *P*)- twist-form (A)
[Synchro(+, +)]

(1*R*, 4*R*, *M*)-twist-form(B)
[Synchro(−, −)]

Stabilization of the twist form B of dilactone I in a polar solvent or in the crystal is unlikely, since a possible decrease in the electrostatic interaction of the dipoles in these media may lead only to a decrease in the degree of twist, but not to inversion of its sign.

The partial mutual compensation of the sums of the dipole moments of the ester groups of rings 1 and 2 in dilactone I is supported by the values of the total μ_D of the calculated structures (Table 2), close in magnitude to the experimental value (μ = 4.27 ± 0.03 D) [11] and the calculated dipole moment of γ-butyrolactone (Table 3).

According to the GED studies [13-15] and calculations by the *ab initio* [16-18] and MM2, MM3 [12] methods, norbornane exists as a completely eclipsed form of C_{2v} symmetry. This is in contrast to bicyclo[2.2.2]octane, in which identical twist forms of D_3 symmetry are preferred (citations in [2]). This means that in stabilization of the preferred A form of dilactone I, the electrostatic interaction predominates over the effect of $n_0-\pi^*$(C=O) conjugation stabilizing the eclipsed forms (similar to norbornadiene V) and the steric interactions (in contrast to dilactone VI).

A compromise between steric interactions and the effect of $n-\pi^*$ conjugation on the one hand and dipole–dipole interactions on the other hand leads to an intermediate twist form for the [2.2.1] bicyclic skeleton of dilactone I (τ_0 = 2.6°, ψ_2 = 271.7°, Table 2) between the eclipsed C_{2v} form of norbornane (τ_0 = 0, ψ_2 = 270°, Table 4) and the synchro(+,+,+)-twist form of dilactone VI (τ_0 = 4.4°, ψ_2 = 273.8°) [2], which is also supported by the large value of the dipole moment (Table 2) and the decrease in the $C_{(3)}\ldots C_{(6)}$ distance (2.732 Å) in molecule I compared with bicycle VI (m= 4.75 D; $C_{(3)}\ldots C_{(6)}$ = 2.760 Å) [2], according to the data for the calculated structures (RHF/6-31G*).

The degree of twist of the rigid [2.2.1] structure of bicycle I probably is responsible for the increase in its strain energy (E_S) (21.04 kcal/mole (MM2)) compared with norbornane (C_{2v}) (15.2 (calc.), 14.4 kcal/mole (exp.)) [18].

Thus the force field of the MM2(91) method, in contrast to MM3(92), more adequately reproduces the *ab initio* model of dilactone I (similar to compounds VI, VII [2]) and may be recommended for stereochemical calculations or as a preliminary approximation for the geometry of homologs of molecule I. The preference for the B form of dilactone I according to the MM3(92) calculation is probably due to a parametrization of the bond dipole moments ($\mu(C(sp^2)-O)$ = 1.47 D, $\mu(C{=}O)$ = 1.86 D) [22] different from the MM2(91) method (0.44 D and 2.60 D) [20].

For comparison, we also optimized the geometry of the dilactone I by the semiempirical quantum chemical methods MNDO [29], AM1 [30], and PM3 [31] using the program MOPAC 5.0. However, the equilibrium structures obtained unsatisfactorily reproduce the *ab initio* model for I. Thus in the semiempirical models, compared with the *ab initio* model for the structure of dilactone I, most of the bonds are lengthened within the range 0.01-0.07 Å, and the values of the bond angles differ by up to 7° (for example, $\Delta\omega_{exo}$ = 13.1° (MNDO), 18.0° (AM1), 18.7° (PM3)). Thus, the semiempirical methods more poorly reproduce the structure of bicycle I than the MM2 method, as in the semiempirical calculations for γ-butyrolactone (citations in [10]).

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