Additions of Group 6A and 7A Electrophilic Reagents to Dimethyl *endo,endo*-Bicyclo[2.2.2]oct-5-ene-2,3-dicarboxylate: Competitive Formation of γ- and δ-Lactones

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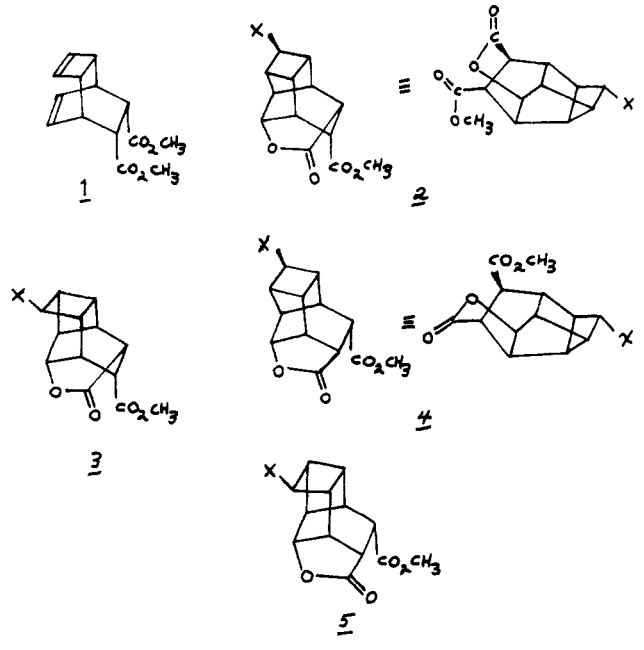
The reaction of dimethyl *endo,endo*-bicyclo[2.2.2]oct-5-ene-2,3-dicarboxylate with chlorine, bromine, iodine, benzeneselenenyl chloride, and benzenesulphenyl chloride has been studied. Under conditions of kinetic control both γ- and δ-lactones are formed, the δ lactone being predominant except in the case of bromine. The thermodynamic product distributions favored the δ-lactones exclusively. A general mechanistic scheme is proposed.

A number of recent investigations of electrophilic additions to dimethyl tricyclo[4.2.2.$0^{2,5}$]decane-3,9-diene-7,8-dicarboxylate, **1**, have indicated that the transannular

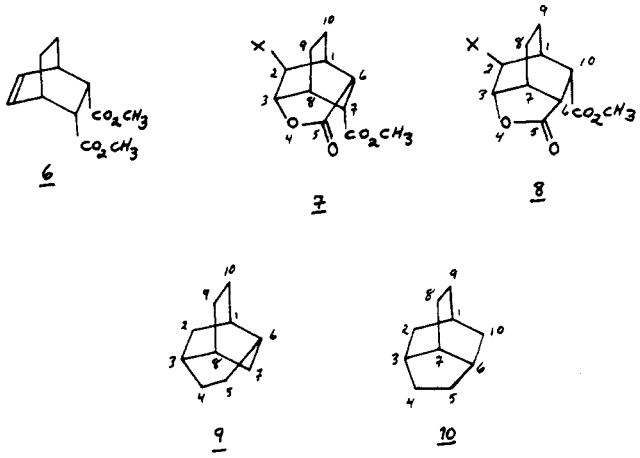


reactions yielding polycyclic hydrocarbons form the δ-lactones[1] **2** and **3** and not the γ-lactones **4** and **5** as previously assigned.[2] The final structure elucidation in these studies rests on X-ray crystallographic techniques. The earlier structure characterizations had been primarily based upon the so-called characteristic carbonyl absorption of five-membered lactone moieties at 1775 cm^{-1} (5.63 μm; dilute CCl_4) vs. 1750 cm^{-1} (5.71 μm; dilute CCl_4) for the six-membered lactone (values in $CHCl_3$ can be ≃10–20 cm^{-1} lower than those in CCl_4).

While the temptation now exists to reassign all of the previous lactone products derived from **1** in terms of the δ-lactone structure, it is not immediately clear if the samples used for X-ray crystallographic analysis are the products of kinetic or thermodynamic control. From the point of view of "chemical intuition" one would have predicted a priori the formation of the γ-lactone on the basis of the known propensity for intramolecular cyclization to favor formation of a five-membered ring under conditions of kinetic control, since on the average the two reacting groups are closer together and have a greater probability of reacting. A complicating feature, however, of these previous studies results from the involvement of transannular π participation between the initial double bonds which in theory could occur in two possible ways, leading to the cross-bonded species **2** and **4** or the *non*-cross-bonded species **3** and **5**. Whereas X-ray crystallographic data and ^1H NMR data clearly indicate the formation of a cross-bonded polycyclic system in the bromination and iodination of **1**, it is not obvious if the resultant internal strains would favor the formation of **2** over **4** under conditions of kinetic control.[3]

In order to ascertain whether or not a competitive process toward formation of δ-lactones instead of γ-lactones exists within systems of this type, we have investigated the reactions of dimethyl *endo,endo*-bicyclo[2.2.2]oct-5-ene-2,3-dicarboxylate, **6**, with a series of electrophilic reagents. This substrate was chosen in view of its close similarity to **1** with respect to intramolecular distances, ring strain, and the absence of complex transannular π interactions.

In principle, this substrate allows for the formation of either a δ-lactone, **7**, or a γ-lactone, **8**, in analogy with **1**.



If one makes the hypothesis, which seems reasonable, that the ring strain inherent in **7** bears the same relationship to the strain energy in **8** that the parent hydrocarbon, tricyclo[4.4.0.$0^{3,8}$]decane (**9**, twistane), has with respect to

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(1) (a) A. Kondo, T. Yamane, T. Ashida, and K. Kanematsu, *J. Org. Chem.*, **43**, 1180 (1978); (b) N. S. Zefirov, V. N. Kirin, A. S. Kozmin, I. V. Bodrikov, K. A. Potekhin, and E. N. Kurkutora, *Tetrahedron Lett.*, 2617 (1978); *Chem. Abstr.*, **90**, 22402 (1979).

(2) (a) T. Sasaki, K. Kanematsu, and A. Kondo, *J. Org. Chem.*, **39**, 2246 (1974); (b) T. Sasuki, K. Kanematsu, A. Kondo, and Y. Nishitani, *ibid.*, **39**, 3569 (1974); (c) N. S. Zefirov, K. N. Sadovaya, V. N. Kirin, A. S. Koz'min, and I. V. Bodrikov, *Zh. Org. Khim.*, **13**(1), 228 (1977); *Chem. Abstr.*, **86**, 155330 (1977); (d) T. Sasaki, K. Kanematsu, and A. Kondo, *J. Chem. Soc., Perkin Trans. 1*, 2516 (1976).

(3) E. Osawa, K. Aigami, and U. Inamoto, *Tetrahedron*, **34**, 509 (1978).

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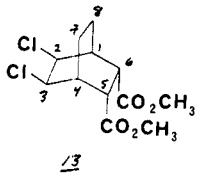
tricyclo[4.3.1.0^{3,7}]decane (**10**, isotwistane), then one would predict **8** to be favored thermodynamically over **7**. This follows from the calculated strain energies of **9** and **10** which are 26.12 and 20.77 kcal mol^{-1}, respectively.[3,4]

Results

Group 7A Electrophiles. The reaction of molecular chlorine with **6** in anhydrous methylene chloride solution at ambient temperature, 22–25 °C, in the dark gives a mixture of four adducts, **11–14**, in a ratio of 57:6:29:8. Lowering the reaction temperature to −40 °C causes a reversal in the proportions of **11** and **12** without affecting the relative amounts of **13** and **14** as is shown in the product ratio 20:42:31:7. On the basis of elemental analysis and mass spectral data it is apparent that species **11** and **12** are polycyclic lactones, whereas **13** and **14** are the dichloro adducts of normal 1,2-addition. No evidence was found for products of Wagner–Meerwein-type rearrangement. Under conditions of thermodynamic control, the lactone **11** is overwhelmingly preferred, the dichloro adducts also decomposing with a loss of chloromethane to yield lactones. We note that in this case and those to be presented shortly, the thermodynamically controlled product composition was determined by allowing the NMR sample tubes to stand at 25 °C until the product distribution, as determined by NMR, remained constant. Similar results were obtained by allowing the reaction solutions to stand for a few hours to a few days after the apparent completion of the primary addition reaction.

Assignment of the two dichloro adducts follows easily from their symmetry characteristics. Thus the products of syn-exo or syn-endo addition possess a plane of symmetry and will give rise to six carbon resonances in their ^{13}C NMR spectra, whereas the analogous species of anti addition should give 12 different resonances.

An examination of the ^{13}C NMR spectra of **13** and **14** clearly allows us to assign **13** as an adduct of syn addition and **14** as a product of anti addition. Assignment of **13** as the product of syn-exo addition follows from the relative chemical shifts of the methylene carbons, C-7,8, and the methine carbons, C-5 and C-6.



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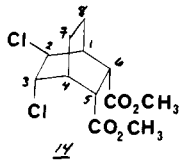

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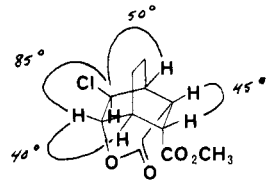
As can be seen from an examination of Tables I and II, the chlorine atoms in **13** exert a strong γ (diamagnetic shielding) shift upon both C-7 and C-8, δ 20.1 vs. 24–25 in their absence. Similarly, the endo chlorine in **14** causes a γ shift of the C-5 carbon, δ 47.2 vs. 51.1 in **13**.

The ^{13}C NMR parameters for a series of model compounds are given in Table II for purposes of comparison.

Our primary attention, however, is aimed at the two lactones **11** and **12**. The infrared spectra of both these species show absorptions at 1810 and 1755 cm^{-1} in dilute CCl_4 indicative of a γ-lactone and a free ester or δ-lactone, respectively. In fact, the lactone absorption at 1810 cm^{-1} is observed at a higher wavenumber than would normally be expected for a five-membered lactone.[16] These observations substantiate those of others with respect to the inadvisability of using carbonyl absorptions for assigning ring size in strained polycyclic compounds.

(4) E. M. Engler, J. D. Andose, and P. v. R. Schleyer, *J. Am. Chem. Soc.*, **95**, 8005 (1973).

Differentiation of **11** and **12** is, however, quite facile through the use of ^{1}H and ^{13}C NMR spectroscopy. An examination of Dreiding molecular models of the δ- and γ-lactones shows dihedral angles between vicinal protons as indicated.



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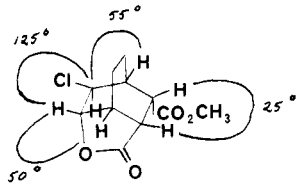

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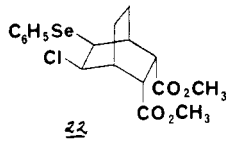
On this basis one anticipates a vicinal coupling constant, $^3J_{HH}$, of 2 Hz or less between protons H-2 and H-3 in the δ-lactones vs. an analogous coupling of approximately 5 Hz in the γ-lactone. The 100-MHz spectrum of **11** has two apparent doublets of doublets at δ 4.74 and 4.61 which are assigned to protons H-2 and H-3, respectively. The low-field resonance shows line splittings of 1.0 and 3.5 Hz, whereas the high-field resonance shows splittings of 1.0 and 5.1 Hz. These data are indicative of a coupling of 1.0 Hz between H-2 and H-3 and therefore allow the assignment of **11** as the δ-lactone: methyl (2*SR*,7*RS*)-2-chloro-4-oxa-5-oxotricyclo[4.4.0.0^{3,8}]decane-7-carboxylate. A similar analysis of the ^{1}H NMR spectrum of **12** ($^3J_{H_2H_3}$ = 4.8 Hz) confirms its assignment as the γ-lactone: methyl (2*SR*,10*RS*)-2-chloro-4-oxa-5-oxotricyclo[4.3.1.0^{3,7}]decane-10-carboxylate.

The ^{13}C NMR parameters of **11** and **12** serve to further substantiate these assignments (see Tables III and IV). The twisted structure of the δ-lactones **7** gives rise to more pronounced γ interactions between the methylene carbons, C-9 and C-10, and the surrounding methine positions, C-2,3,6,7, than can be obtained from the γ-lactones **8** with respect to the analogous carbons, C-8 and C-9 relative to C-2,3,6,10. As can be seen from Tables III and IV, C-9 and C-10 in **11** resonate at higher field than C-8 and C-9 in species **12**: δ 19.6 and 14.3 vs. 21.0 and 18.4.

In a similar manner we were able to assign structures to the four adducts **15–18** derived from the reaction of bromine with **6**. In contrast to our observations with chlorine, the γ-lactone **16** was favored under conditions of kinetic control (see Table V). But once again the δ-lactone proved to be thermodynamically most stable.

The iodination of **6** was anomalous in that only the δ-lactone **19** was observable and isolable. Assignment in this case was based on the close similarity in ^{1}H and ^{13}C NMR parameters.

Group 6A Electrophiles. The reaction of benzeneselenenyl chloride with **6** in anhydrous methylene chloride gives a mixture of four adducts, **20–23**, in the ratio 68:25:3:4. In accord with our previously established criteria for structural assignments, the two major products are identified as the δ- and γ-lactones **20** and **21**, respectively. Similarly, the minor components may be assigned as dimethyl (2*SR*,3*RS*,5*SR*,6*RS*)- and dimethyl (2*SR*,3*SR*,5*SR*,6*RS*)-2-(phenylseleno)-3-chlorobicyclo[2.2.2]octane-5,6-dicarboxylates **22** and **23**, respectively.



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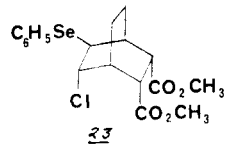

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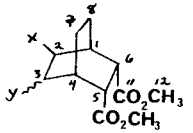
This latter result is of special interest, since we have observed here only the second reported example of non-

Table I. Carbon-13 NMR Parameters for a Series of Dimethyl (2*SR*,3*RS*,5*SR*,6*RS*)- and (2*SR*,3*SR*,5*SR*,6*RS*)-2,3-Disubstituted-bicyclo[2.2.2]octane-5,6-dicarboxylates



(2SR, 3RS) = x and y cis

(2SR, 3RS) = x and y trans

substnts X	substnts Y	rel config	compd no.	chemical shifts, ppm C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}	C_{12}	other
Cl	Cl	2(*SR*),3(*RS*)	**13**	36.6	67.3	67.3	36.6	51.1	51.1	20.1	20.1	172.3	53.9	172.3	53.9	
		2(*SR*),3(*SR*)	**14**	35.9	68.5	68.6	35.8	47.2	52.3	25.3	20.2	172.1	53.8	172.3	54.2	
Br	Br	2(*SR*),3(*RS*)	**17**	33.6	66.9	66.9	33.6	52.0	52.0	20.9	20.9	171.6	52.0	171.6	52.0	
		2(*SR*),3(*SR*)	**18**	32.8	68.2	67.9	32.7	46.3	51.9	24.3	20.8	171.8	52.0	171.8	52.0	
C_6H_5Se	Cl	2(*SR*),3(*RS*)	**22**	32.3	59.8	61.6	36.0	43.5	44.8	20.0	18.5	171.6	52.0	171.6	52.4	134.4, 129.0, 127.5
		2(*SR*),3(*SR*)	**23**	31.2	50.8	69.3	37.0	40.5	44.1	22.9	15.1	172.3	48.0	172.3	48.0	132.6, 129.5, 127.4

Table II. Carbon-13 NMR Parameters for a Series of Model Compounds with a Bicyclo[2.2.2]octane Framework

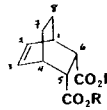
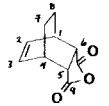
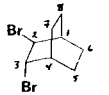
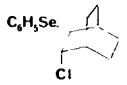
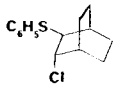
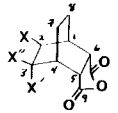
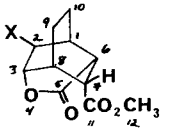
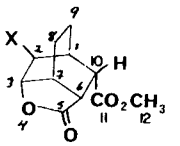
compd		chemical shifts (ppm) and coupling constants (Hz) C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}	other
	δ	29.6	134.3	134.3	29.6	25.8	25.8	25.8	25.8				
	$^1J_{CH}$	134.0	164.5		134.0	131.0							
	$^nJ_{CH}$					6.2							
						R = C^9H_3							
	δ	32.1	131.9	131.9	32.1	47.1	47.1	24.1	24.1	172.8	51.0		
	$^1J_{CH}$	140.2	165.9			133.5		132.0			146.8		
	$^2J_{CH}$	6.2	3.4										
						R = $C^9H_2C^{10}H_3$							
	δ	32.1	131.7	131.7	32.1	47.1	47.1	24.1	24.1	172.1	59.6	13.5	
	$^1J_{CH}$	140.1	166.8			132.8		131.6			147.1	127.6	
	$^2J_{CH}$					2.5					4.2	2.0	
	δ	31.6	133.0	133.0	31.6	44.7	44.7	22.9	22.9	172.9			
	$^1J_{CH}$	143.8	167.4			137.9		135.0					
	$^2J_{CH}$	6.2											
	δ	35.0	61.4	61.4	35.0	19.3	25.6	25.6	19.3				
	$^1J_{CH}$	140.7	160.8			133.0	130.2						
	δ	31.5	53.9	66.8	34.1	18.6	26.4	25.1	20.3				
	$^1J_{CH}$	138.1	145.6	139.3	132.2	129.0	129.0	129.4	132.5				
	$J_{Se,C}$		68.2	17.8									
	δ	30.5	58.0	65.7	33.9	18.7	25.8	24.9	19.1				132.9, 133.2 129.0, 129.5
						X = X′ = Br; X″ = H							
	δ	36.5	54.4	54.4	36.5	44.2	44.2	17.8	17.8	171.4			
						X = X″ = Br; X′ = H							
	δ	35.3	54.2	54.2	35.5	40.8	44.6	26.3	18.6	171.4			
						X = C_6H_5Se; X″ = H; X′ = Cl							
	δ	31.2	51.3	67.7	37.1	40.3	42.2	20.2	15.1	172.8			

Table III. Carbon-13 NMR Parameters for a Series of Methyl (2*SR*,7*RS*)-2-Substituted-4-oxa-5-oxotricyclo[4.4.0.$0^{3,8}$]decane-7-carboxylates



X	compd no.	chemical shifts, ppm											other
		C_1	C_2	C_3	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}	C_{12}	
Cl	11	32.7	56.9	83.5	177.1	42.9	39.6	36.6	19.6	14.3	172.3	52.6	
Br	15	33.1	48.7	83.7	176.0	39.5	43.3	36.7	21.5	14.4	171.6	52.0	
I	19	31.5	39.8	85.7	176.4	39.6	42.8	36.7	22.7	14.7	171.3	52.2	
C_6H_5Se	20	31.0	42.1	83.2	176.7	43.9	40.3	36.9	22.7	15.0	171.9	52.0	
C_6H_5S	26	30.3	45.9	81.9	176.5	43.5	40.3	36.9	21.0	14.8	172.0	52.1	
4-$CH_3OC_6H_4S$		30.6	46.9	81.9	176.7	43.7	40.5	37.0	21.0	15.0	172.1	52.2	56.3, CH_3OAr
2,4-$(NO_2)_2C_6H_3S$		30.3	44.6	81.5	176.3	43.7	40.3	37.0	20.9	14.8	172.4	52.5	143.9, 145.3, 127.9, 121.9
2-NO_2-4-ClC_6H_3S		30.3	44.1	81.8	176.3	43.9	40.4	37.0	21.0	14.9	172.2	52.4	134.3, 128.2, 126.3 146.5, 135.5, 131.3
2-$NO_2C_6H_4S$		30.4	43.9	82.0	176.5	43.9	40.5	37.0	21.1	14.9	172.2	52.4	146.4 (s), 135.0 (s), 134.3 (d) 127.5, 126.4, 125.4
2-NO_2-4-$CH_3C_6H_3S$		30.4	44.0	82.0	176.5	44.0	40.5	37.0	21.1	14.9	172.2	52.3	20.5, $CH_3C_6H_3NO_2S$ 135.2, 127.7 126.5, 146.5
2-NO_2-4-$CH_3OC_6H_3S$		30.5	44.7	82.0	176.5	43.9	40.5	37.1	21.1	14.9	172.1	52.3	56.0, OCH_3 157.7 s(m), 147.8 s(m), 129.6 d(d), 121.6 d(dd), 110.5 d(dd), 124.7 s(m)
2-CH_3-4-$NO_2C_6H_3S$		30.5	44.1	82.1	176.3	43.7	40.4	37.0	21.3	14.9	172.2	52.4	20.2, $CH_3C_6H_3NO_2S$ 122.0, 125.2, 124.6 144.3, 136.8

Table IV. Carbon-13 NMR Parameters for a Series of Methyl (2*SR*,10*RS*)-2-Substituted-4-oxa-5-oxotricyclo[4.3.1.$0^{3,7}$]decane-10-carboxylates



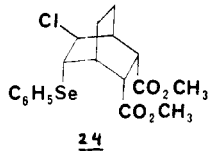
X	compd no.	chemical shifts, ppm											other
		C_1	C_2	C_3	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}	C_{12}	
Cl	12	35.2	63.1	78.1	175.2	41.0	36.6	21.0	18.4	44.3	173.2	51.1	
Br	16	35.9	56.1	78.7	175.0	41.2	37.0	24.3	19.5	43.5	172.5	52.0	
C_6H_5Se	21	33.1	47.8	75.0	175.7	41.8	36.3	24.5	20.5	44.1	172.9	51.6	
C_6H_5S	27	32.4	50.8	74.4	175.5	41.8	36.5	24.2	19.5	43.4	173.1	51.4	
2,4-$(NO_2)_2C_6H_3S$		31.5	49.5	73.1	175.2	41.9	37.7	24.0	20.3	43.0	173.4	52.0	
2-NO_2-4-ClC_6H_3S		31.5	49.3	73.7	175.4	41.9	37.0	24.2	20.0	43.3	173.4	51.9	
2-$NO_2C_6H_4S$		31.6	49.1	73.8	175.5	41.9	37.0	24.2	20.1	43.4	173.5	51.9	146.4, 135.0, 133.8 128.9, 125.9, 124.8
2-NO_2-4-$CH_3C_6H_3S$		31.6	49.1	73.9	175.3	41.9	36.8	24.2	20.0	43.5	173.5	51.0	20.5, $CH_3C_6H_3NO_2S$ 134.8, 128.9 126.0, 136.1
2-NO_2-4-$CH_3OC_6H_3S$		31.7	49.5	73.8	175.5	41.9	37.0	24.2	19.9	43.4	173.6	51.8	55.0, CH_3OAr 126.9, 147.5, 157.2
2-CH_3-4-$NO_2C_6H_3S$		31.9	49.1	74.2	175.7	42.0	36.8	24.4	20.0	43.4	173.3	51.9	20.2, $CH_3C_6H_3NO_2S$ 145.1, 126.1, 131.3 124.1, 121.6

Table V. Initially Observed Product Distributions for the Addition of Various Electrophiles to Dimethyl *endo,endo*-Bicyclo[2.2.2]oct-5-ene-2,3-dicarboxylate in Methylene Chloride Solution at 25 °C

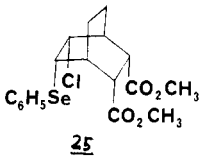
	ratio of products			
			1,2-adducts	
electrophile	δ-lactone	γ-lactone	cis	trans
Cl_2	57	6	29	8
Br_2	16	56	18	9
I_2	100	0	0	0
C_6H_5SeCl	68	25	3	4
C_6H_5SCl	78	22	0	0
$4\text{-}CH_3OC_6H_4SCl$	≤5	≥95	0	0
$2,4\text{-}(NO_2)_2C_6H_3SCl$	69	31	0	0
$2\text{-}NO_2\text{-}4\text{-}ClC_6H_3SCl$	68	32	0	0
$2\text{-}NO_2C_6H_4SCl$	78	22	0	0
$2\text{-}NO_2\text{-}4\text{-}CH_3C_6H_3SCl$	74	26	0	0
$2\text{-}CH_3\text{-}4\text{-}NO_2C_6H_3SCl$	77	23	0	0
$2\text{-}NO_2\text{-}4\text{-}CH_3OC_6H_3SCl$	9	91	0	0

stereospecific addition of an areneselenenyl chloride to an olefin.[5]

Alternative structures for **22** such as **24** and **25** may be ruled out on the basis of its ^{13}C NMR spectrum. The



24



25

chemical shifts of the methylene carbon ethano bridge, C-7 and C-8, in **22** resonate at δ 20.0 and 18.5, respectively (Table III), and thus are shielded compared to the analogous carbons in the parent hydrocarbon (see Table II) in agreement with the expected γ effect. The difference in the chemical shifts of C-7 and C-8 is also smaller than that observed in the adduct derived from anti addition, **23** (Δ = 1.5 vs. 7.8 ppm). Furthermore, a comparison of the methine carbons at C-5 and C-6 between **22** and **23** (Δ = 1.3 vs. 3.6 ppm) serves to confirm the assignment. One notes that were an adduct of syn-endo addition such as **25** formed, the resonances for carbons C-5 and C-6 should be much more shielded, appearing at approximately δ_{calcd} 38–40.

In contrast to the above, the reaction of benzenesulphenyl chloride with **6** under equivalent reaction conditions yields no adducts of simple syn or anti 1,2-addition. The only observable and isolable products were the δ- and γ-lactones **26** and **27**. Configurational assignments were made as above.

In order to more fully understand the probable nature of the intermediates and transition states leading to the formation of these adducts, we have run a series of experiments in which the electrophilicity of the sulphenyl chloride is varied through changes of the substituents on its phenyl ring. These results are shown in Table V.

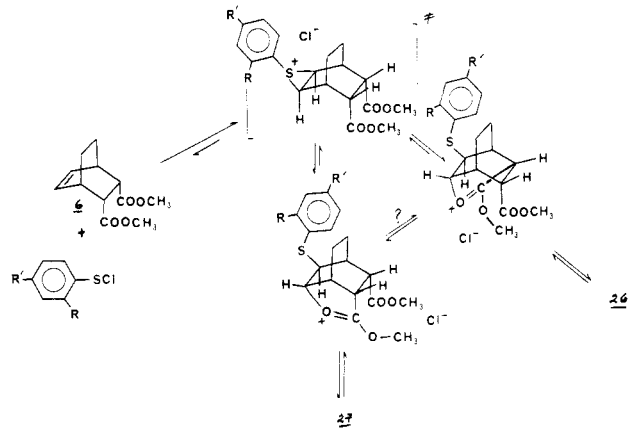
Of note is the absence of simple 1,2-addition products and the complete reversal of chemoselectivity on substituting a methoxyl group for methyl in the para position of the sulphenyl chloride.

The presence of the ortho or para nitro substituents on the main series of arenesulphenyl chlorides serves only to slow down the rate of addition and subsequent isomerizations from a few minutes or hours to a few days.

In this respect we observed that for both 4-methoxybenzenesulphenyl chloride and benzeneselenenyl chloride

(5) D. G. Garratt, *Can. J. Chem.*, 56, 2184 (1978).

Scheme I



subsequent isomerizations between γ- and δ-lactones were competitive with but somewhat slower than the primary addition reaction. In both of these cases it was necessary to measure initial product distributions at a point corresponding to the reaction reaching 5–10% of completion.

Discussion

Within the limits of our initial objectives, these results indicate that the formation of γ- and δ-lactones in polycyclic systems of this type is competitive and that the δ-lactone is thermodynamically preferred despite an *apparently* larger amount of strain energy. The utility of NMR, particularly ^{13}C NMR, for assigning configuration in these types of compounds is amply demonstrated. Of greater interest, however, are the mechanistic questions raised in light of the product distributions shown in Table V.

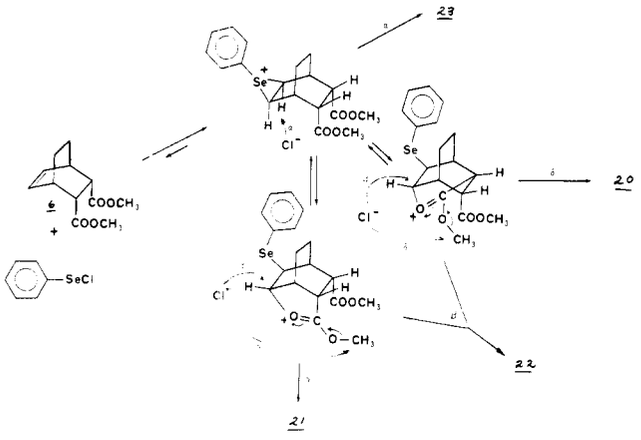
An examination of Table V shows a number of trends. First of all, lactonization is favored in all cases over 1,2-addition. With the exception of bromine, 4-methoxybenzenesulphenyl chloride, and 2-nitro-4-methoxybenzenesulphenyl chloride, the δ-lactone is preferentially formed, the δ/γ ratios varying from 2.1:1 to 9:1. The result with iodine is probably anomalous, since iodine is known to form a series of equilibrating complexes with alkenes, the position of the equilibria depending upon the structure of the alkene, the solvent, and the temperature.[6] In the three cases where the γ-lactone is preferentially formed under conditions of kinetic control, bromination shows the lowest selectivity, γ/δ ratio of 3.5:1, and the sulphenyl chlorides show the highest, 19:1.

The data obtained from the series of arenesulphenyl chlorides is a priori the most instructive since essentially identical steric environments should be found within the vicinity of the reactive sites. We were thus able to investigate the effect of varying substituents on the electrophile, thereby changing the electrophilicity, as is reflected in the bridging ability or degree of neighboring-group participation of the arylthio moiety, while holding the second potential neighboring group, in this case the ester carbonyl, constant. Of particular importance is the fact that the ester carbonyl may stabilize charge development at the reaction site in either of two ways, leading to, respectively, the two types of lactone.

An important aspect of the mechanism of sulphenyl chloride additions is the presence of a sulphur-bridged intermediate, a thirranium ion, prior to the product-determining transition state, as is shown in Scheme I.[7] It

(6) G. H. Schmid and D. G. Garratt in "The Chemistry of Double-Bonded Functional Groups, Supplement A", Part 2, S. Patai, Ed., Wiley, New York, 1977, p 785.

Scheme II



is our belief that equilibration between the first-formed thiiranium ion intermediate and the two subsequent oxacarbonium ion intermediates or transition states can account for the observed product distributions.

Examination of Dreiding models and a consideration of the orientation of the orbitals necessary for intramolecular ring closure suggest that considerable bond distortion would be required to bring about a collinear approach of the ester carbonyl to form a δ-lactone from a thiiranium ion or any other three-membered-ring intermediate. No such constraints would appear to affect the formation of the γ-lactone.[8,17]

The intriguing aspect of this hypothesis is the suggestion that the γ-lactones 8 will be preferentially formed from highly stable bridged intermediates, such as is surely the case for 4-methoxy- and 2-nitro-4-methoxybenzenesulphenyl chlorides. Alternatively, competitive formation of δ-lactones should be anticipated when opening of the bridged ion (e.g., thiiranium ion) to a classical carbonium ion at C-3, or to either or both of the oxacarbonium ions, yields a more stable species. If this scenario is correct, the oxacarbonium ions is Scheme I are more stable than the corresponding thiiranium ion when the remote substituents on the phenyl ring of the sulphenyl chloride are more electron withdrawing than methyl.

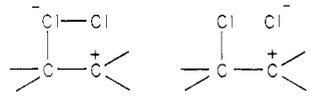
In summary, these data indicate a definitive interplay of two neighboring-group effects in the additions of arenesulphenyl chlorides to 6, wherein the kinetically controlled product distributions reflect the effect of increasing electron demand upon the product-determining transition state.

The addition of benzeneselenenyl chloride to 6 is readily interpreted in the same manner as for arenesulphenyl chlorides above, as is shown in Scheme II. The better neighboring-group ability of selenium relative to sulphur may account for a longer lived bridged species, the seleniranium ion, thus allowing attack by chloride ion on the endo face of the intermediate to compete with intramolecular ring closure to give the two oxacarbonium ions.[9] Attack by chloride ion on the exo face of these oxacarbonium ions will then account for the adduct of syn addition.

The absence of 1,2-addition products from the analogous reaction of benzenesulphenyl chloride suggests a lower activation barrier toward collapse to lactone products for the sulphur electrophiles.

Conceptually the reactions of chlorine and bromine with 6 require a more varied reaction hypersurface. In both of these cases it is necessary to account for larger amounts of 1,2-addition, 37 and 28%, respectively, and a reversal in the proportions of δ- and γ-lactones. The latter aspect is most easily resolved, since bromine is a better neighboring group than chlorine and thus by our previous arguments should give a preponderance of γ-lactone.

The chlorination of alkenes capable of forming stabilized cations frequently results in dichloro adducts formed by preferential syn addition in the absence of external chloride ion.[10a] Results of this type have generally been accommodated by a mechanism involving the initial formation of a zwitterion or intimate ion pair as the precursor to the syn adduct (I and II), followed by isomerization to a



I II

chloriranium ion, the probable precursor to the adduct of anti addition. It is furthermore believed that multiple intermediates, all rather close in energy, are to be found during the chlorination of alkenes and that under some circumstances reactions of these intermediates with nucleophiles can occur before they reach their most stable conformation. We therefore feel that further mechanistic speculation is unwarranted at this time.

In contrast to chlorine, bromine is usually observed to add stereoselectively in the anti sense.[10b] The presence of syn adducts is generally considered the result of steric inhibition to nucleophilic attack in the anti sense or to the presence of nonclassical ions on the reaction hypersurface. While the presence of a steric effect in the form of the di-*endo*-carboxylate functionalities is quite obvious,[11] we have little information with respect to nonclassical ionic structures. This latter effect, however, seems of little importance in view of the absence of rearrangement products. It is of note that bicyclo[2.2.2]oct-2-ene and bicyclo[2.2.2]oct-5-ene-2,3-dicarboxylic anhydride both give products of Wagner–Meerwein-like rearrangement on bromination. These data are then indicative of the presence of bromo analogues of the oxacarbonium ions shown in Schemes I and II on the reaction hypersurface and demonstrate that these ions are of greater stability than the possible nonclassical structures.

Experimental Section

Melting points were determined on a Fisher-Johns block and are reported uncorrected. ^{1}H NMR spectra were determined on Varian Associates T-60 and HA-100 spectrometers. ^{13}C NMR spectra were determined by using a Varian FT80 spectrometer with a broad-band probe operated in the Fourier transform mode at 20.000 MHz. Solutions were in chloroform-*d* containing Me_4Si. Chloroform was used as both an internal reference and a lock signal. All chemical shifts are expressed in parts per million from internal Me_4Si (δ). Infrared spectra were recorded on a Unicam 1100 spectrometer, using matched NaCl 0.1071-mm cavity cells, as CCl_4 solutions. All analytical and preparative TLC separations

(7) (a) G. H. Schmid and D. G. Garratt in "The Chemistry of Double-Bonded Functional Groups, Supplement A", Part 2, S. Patai, Ed., Wiley, New York, 1977, pp 828–58; (b) N. Kharasch and C. M. Buess, *J. Am. Chem. Soc.*, 71, 2724 (1949); (c) M. de Moura Campos, *ibid.*, 76, 4480 (1954).

(8) (a) G. Stork, L. D. Cams, and D. R. Coulson, *J. Am. Chem. Soc.*, 96, 5268, 5270 (1974); (b) J. E. Baldwin, J. Cutting, W. Dupont, L. Kruse, L. Silberman, and R. C. Thomas, *J. Chem. Soc., Chem. Commun.*, 736 (1976); (c) J. E. Baldwin, *ibid.*, 734 (1976); (d) G. Stork and J. F. Cohen, *J. Am. Chem. Soc.*, 96, 5270 (1974); (e) L. Tenud, S. Faroog, J. Seible, and A. Eschenmoser, *Helv. Chim. Acta*, 53, 2059 (1970).

(9) S. P. McManus, and D. H. Lam, *J. Org. Chem.*, 43, 650 (1978).

(10) (a) G. H. Schmid and D. G. Garratt in "The Chemistry of Double-Bonded Functional Groups, Supplement A", Part 2, S. Patai, Ed., Wiley, New York, 1977, pp 754–63; (b) G. H. Schmid and D. G. Garratt, *ibid.*, pp 764–85.

(11) (a) H. Kwait and L. Kaplan, *J. Am. Chem. Soc.*, 75, 3356 (1953); 76, 4078 (1954); (b) C. D. Ver Nooy and C. S. Ronestredt, Jr., *J. Am. Chem. Soc.*, 77, 3583 (1955).

were performed on Analtech or Macherey-Nagel precoated plates (silica gel GF). Visualization of the TLC spots was accomplished by I_2, UV irradiation (254 nm), and phosphomolybdic acid/EtOH. R_f values are given as the distance traveled by the spot, to its center, divided by total distance traveled by the solvent front at 25 °C. Yields were determined by weighing the collected fractions.

Benzeneselenenyl chloride was commercially available from Aldrich and was recrystallized from CCl_4: mp 63.7–64.5 °C (lit.[18] 64 °C); UV (n → π*, Se–Cl) λ_{max} 433 nm (ε 264 L mol^{-1} cm^{-1}).

Benzenesulphenyl chloride was prepared from the commercially available thiol by direct chlorination in CCl_4 at 4 °C; bp 72 °C (4 mm) [lit.[12] bp 60 °C (3 mm)].

2,4-Dinitrobenzenesulphenyl chloride was prepared by the method of Lawson and Kharasch from bis(2,4-dinitrophenyl) disulfide and was recrystallized from CCl_4; mp 96–96.5 °C (lit.[13] mp 97–98 °C).

2-Nitro-4-chlorobenzenesulphenyl chloride was prepared by the method of Turner and Conner using *p*-dichlorobenzene (Aldrich) as starting material and was recrystallized from 1:1 chloroform–CCl_4; mp 98 °C (lit.[14] mp 97.5–98 °C).

2-Nitrobenzenesulphenyl chloride was available from Aldrich and was recrystallized from CCl_4; mp 76 °C (lit.[12] mp 74.5–75 °C).

2-Nitro-4-methylbenzenesulphenyl chloride was prepared from the analogous aniline by the procedure of Zincke and Röse and was recrystallized from CCl_4; mp 89–90 °C (lit.[15] mp 90 °C).

2-Nitro-4-methoxybenzenesulphenyl chloride was prepared from the analogous aniline as above and crystallized as brilliant orange needles from CCl_4; mp 106–107 °C.

***endo*-Bicyclo[2.2.2]oct-5-ene-2,3-dicarboxylic anhydride** was prepared by the cycloaddition of maleic anhydride with 1,3-cyclohexadiene (Aldrich) in benzene solution under reflux and was recrystallized from benzene: mp 146–147 °C (lit.[19] mp 144–147 °C); IR 1975, 1870 cm^{-1}; ^{1}H NMR 6.28 (m, 2 H), 3.22 (br s, 2 H), 2.98 (s, 2 H), 1.55 (A_2B_2, 4 H); ^{13}C NMR, see Table II.

Dimethyl *endo,endo*-bicyclo[2.2.2]oct-5-ene-2,3-dicarboxylate, 6, was prepared from the corresponding anhydride via esterification in HCl/MeOH and was recrystallized from MeOH: mp 64–67 °C; IR 1750 cm^{-1}; ^{1}H NMR 6.35 (m, 2 H), 3.42 (s, 6 H), 3.00 (br s, 2 H), 2.92 (br m, 2 H), 1.52 (A_2B_2, 4 H); ^{13}C NMR, see Table II.

Bicyclo[2.2.2]oct-2-ene was available commercially from Chemical Samples Co. and was used without further purification.

Product Studies. Reactions were carried out in both the presence and the absence of light, oxygen, and/or isoamyl nitrite. No difference in product composition was observed with respect to these variables.

General Procedure. To a quantity of **6** (e.g., 0.3601 g, 1.61 mmol) in 25 mL of methylene chloride was added dropwise a solution containing 1 molar equiv of the electrophile predissolved in 25 mL of the solvent. Upon completion of the reaction, the solvent was removed by rotary evaporation at room temperature. Product distributions determined from these samples corresponded within ±2% with a series of control reactions carried out on a scale suitable for NMR monitoring. TLC on silica gel using CH_2Cl_2 as elutant gives R_f values of approximately 0.58, 0.52, 0.36–0.40, and 0.07 for the anti-1,2-adducts, γ-lactones, δ-lactones, and syn-1,2-adducts, respectively, irrespective of the nature of the electrophile.

Melting Points of Isolated Species. Chloro adducts: **11**, 122–124 °C; **13**, oil; **14**, oil. Bromo adducts: **15**, 132–133 °C; **17**, oil; **18**, oil. Iodo adduct: **19**, 125–127 °C. Phenylseleno adducts: **20**, 114–116 °C; **21**, 118–125 °C; **22**, oil; **23**, oil. Arylthio δ-lactones: aryl = C_6H_5, 109–112 °C; 2,4-$(NO_2)_2S_6H_3$, 198–200 °C; 2-NO_2, 4-ClC_6H_3, 189–191 °C; 2-$NO_2C_6H_4$, 128–129 °C; 2-NO_2-4-$CH_3C_6H_3$, 155–157 °C; 2-NO_2-4-$CH_3OC_6H_3$, 166–169 °C. All samples gave the correct elemental analysis and expected mass spectral fragmentations.

Acknowledgment. Continued financial support from the Natural Science and Engineering Research Council of Canada is gratefully acknowledged, as is the Province of Ontario Scholarship to P.L.B.

Registry No. *meso*-**6**, 4545-84-0; (±)-**11**, 72443-88-0; (±)-**12**, 72443-89-1; *meso*-**13**, 72443-90-4; (±)-**14**, 72496-15-2; (±)-**15**, 72443-91-5; (±)-**16**, 72443-92-6; *meso*-**17**, 72443-93-7; (±)-**18**, 72496-16-3; (±)-**19**, 72443-94-8; (±)-**20**, 72443-95-9; (±)-**21**, 72443-96-0; (±)-**22**, 72443-97-1; (±)-**23**, 72496-17-4; (±)-**26**, 72443-98-2; (±)-**27**, 72443-99-3; bicyclo[2.2.2]oct-2-ene, 931-64-6; diethyl *endo,endo*-bicyclo[2.2.2]oct-5-ene-2,3-dicarboxylate, 72496-18-5; *endo*-bicyclo[2.2.2]oct-5-ene-2,3-dicarboxylic anhydride, 24327-08-0; (±)-*exo,endo*-2,3-dibromobicyclo[2.2.2]octane, 72444-00-9; (±)-*exo,endo*-2-(phenylselenyl)-3-chlorobicyclo[2.2.2]octane, 72444-01-0; (±)-*exo,endo*-2-(phenylthio)-3-chlorobicyclo[2.2.2]octane, 72444-02-1; (±)-*exo,endo*-5,6-dibromo-*endo*-bicyclo[2.2.2]octane-2,3-dicarboxylic anhydride, 72444-03-2; (±)-*exo,exo*-5,6-dibromo-*endo*-bicyclo[2.2.2]octane-2,3-dicarboxylic anhydride, 72496-19-6; (±)-5-*endo*-chloro-6-*exo*-(phenylselenyl)-*endo*-bicyclo[2.2.2]octane-2,3-dicarboxylic anhydride, 72444-04-3; methyl (2*SR*,7*RS*)-2-[(4-methoxyphenyl)thio]-4-oxatricyclo[4.4.0.0^{3,8}]deca-5-one-7-carboxylate, 72444-05-4; methyl (2*SR*,7*RS*)-2-[(2,4-dinitrophenyl)thio]-4-oxatricyclo[4.4.0.0^{3,8}]deca-5-one-7-carboxylate, 72453-31-7; methyl (2*SR*,7*RS*)-2-[(4-chloro-2-nitrophenyl)thio]-4-oxatricyclo[4.4.0.0^{3,8}]deca-5-one-7-carboxylate, 72444-06-5; methyl (2*SR*,7*RS*)-2-[(2-nitrophenyl)thio]-4-oxatricyclo[4.4.0.0^{3,8}]deca-5-one-7-carboxylate, 72444-07-6; methyl (2*SR*,7*RS*)-2-[(4-methyl-2-nitrophenyl)thio]-4-oxatricyclo[4.4.0.0^{3,8}]deca-5-one-7-carboxylate, 72444-08-7; methyl (2*SR*,7*RS*)-2-[(4-methoxy-2-nitrophenyl)thio]-4-oxatricyclo[4.4.0.0^{3,8}]deca-5-one-7-carboxylate, 72444-09-8; methyl (2*SR*,7*RS*)-2-[(2-methyl-4-nitrophenyl)thio]-4-oxatricyclo[4.4.0.0^{3,8}]deca-5-one-7-carboxylate, 72453-32-8; methyl (2*SR*,10*RS*)-2-[(2,4-dinitrophenyl)thio]-4-oxatricyclo[4.3.1.0^{3,7}]deca-5-one-10-carboxylate, 72444-10-1; methyl (2*SR*,10*RS*)-2-[(4-chloro-2-nitrophenyl)thio]-4-oxatricyclo[4.3.1.0^{3,7}]deca-5-one-10-carboxylate, 72444-11-2; methyl (2*SR*,10*RS*)-2-[(2-nitrophenyl)thio]-4-oxatricyclo[4.3.1.0^{3,7}]deca-5-one-10-carboxylate, 72444-12-3; methyl (2*SR*,10*RS*)-2-[(4-methyl-2-nitrophenyl)thio]-4-oxatricyclo[4.3.1.0^{3,7}]deca-5-one-10-carboxylate, 72444-13-4; methyl (2*SR*,10*RS*)-2-[(4-methoxy-2-nitrophenyl)thio]-4-oxatricyclo[4.3.1.0^{3,7}]deca-5-one-10-carboxylate, 72444-14-5; methyl (2*SR*,10*RS*)-2-[(2-methyl-4-nitrophenyl)thio]-4-oxatricyclo[4.3.1.0^{3,7}]deca-5-one-10-carboxylate, 72444-15-6; benzeneselenenyl chloride, 5707-04-0; benzenesulfenyl chloride, 931-59-9; 2,4-dinitrobenzenesulfenyl chloride, 528-76-7; 2-nitro-4-chlorobenzenesulfenyl chloride, 4153-06-4; 2-nitrobenzenesulfenyl chloride, 7669-54-7; 2-nitro-4-methylbenzenesulfenyl chloride, 4288-90-8; 2-nitro-4-methoxybenzenesulfenyl chloride, 4153-07-5; maleic anhydride, 108-31-6; 1,3-cyclohexadiene, 592-57-4.

(12) N. Kharasch, *Intra-Sci. Chem. Rep.*, 1(4), 340 (1969).
(13) D. Lawson and N. Kharasch, *J. Org. Chem.*, **24**, 857 (1959).
(14) R. A. Turner and R. Conner, *J. Am. Chem. Soc.*, **69**, 1009 (1947).
(15) T. Zincke and H. Röse, *Justus Liebigs Ann. Chem.*, **406**, 103, 127 (1914).
(16) Although we were unable to obtain a sample of **12** which was not contaminated with **11**, samples containing as little as 10% **11** were isolable via preparative TLC and proved suitable for spectral analysis.
(17) The orbitals of importance in this regard are those which are associated with the carbons of the thiiranium ion, C-2,3, or other three-membered rings. A pertinent discussion of these factors is given in ref 8.
(18) D. G. Foster, *J. Am. Chem. Soc.*, **55**, 822 (1933).
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