Table III. Melting Points and Yields for 7, 8, 9, 10

compd[a]	formula	yield, %	mp, °C
7a	$C_{16}H_{16}NO_2S_2Cl_3$	77	91.5-93
7b	$C_{20}H_{18}NO_2S_2Cl_3$	89	131-132
8a	$C_{22}H_{22}NO_2S_2Cl$	60	119-120.5
8b	$C_{26}H_{24}NO_2S_2Cl$	70	166-167
8c	$C_{23}H_{24}NO_2S_2Cl$	90	109-110
9a	$C_{21}H_{20}N_2O_4S_2$	81	142.5-143.5
9b	$C_{25}H_{22}N_2O_4S_2$	69	167.5-168.5
9c	$C_{22}H_{22}N_2O_4S_2$	80	127.5-129
10a	$C_{21}H_{19}N_3O_6S_2$	63	134-136
10b	$C_{25}H_{21}N_3O_6S_2$	80	205-206.5
10c	$C_{22}H_{21}N_3O_6S_2$	56	152-154

[a] Satisfactory combustion analytical data (±0.4% in C, H, and N) were reported for these compounds.

ature. 4-Chloro-2-methylbenzenesulfenyl chloride was prepared by chlorination of 5-chloro-2-thiocresol using a literature procedure.[13]

***p*-Toluenesulfonamides 4, 5, and 6.** The appropriate amine (10.0 g) was reacted with 1 equiv of *p*-toluenesulfonyl chloride in the presence of 1 equiv of triethylamine, and the product sulfonamide was recrystallized from methanol: **4**, mp 97-99 °C, $[\alpha]^{23}_D$ +72° (*c* 0.4, EtOH); **5**, mp 122.5-123.5 °C, $[\alpha]^{23}_D$ +7.5° (*c* 0.4, EtOH); **6**, mp 64-66 °C.

Sulfenylsulfonamides 7, 8, 9, and 10. A solution of 1-3 g of the appropriate sulfonamide in 150 mL of anhydrous ether was treated with 1 equiv of *n*-butyllithium, and an ethereal solution of 1 equiv of the sulfenyl chloride was added dropwise. The reaction mixture was filtered, washed with water, and dried, and the solvent was removed in vacuo. Methanol was added to induce crystallization and the product recrystallized from benzene, hexane, cyclohexane, 2-propanol, or a mixture of these solvents. Melting points, yields, and analytical data for these compounds are given in Table III.

(*R*)-(+)-*N*-[1-(1-Naphthyl)ethyl]trichloromethanesulfenamide (12). An ethereal solution of 3.25 g (0.0175 mol) of trichloromethanesulfenyl chloride was added dropwise to an ethereal solution of 3.0 g (0.0175 mol) of amine and 1.77 g (0.0175 mol) of triethylamine. After being stirred for 3 h, the reaction mixture was filtered, washed with water, and dried, and the solvent was removed in vacuo. The product was recrystallized from hexane/2-propanol (6:1): mp 64-65.5 °C; NMR (CCl_4) δ 1.66 (CH_3CH, d, J = 6.5 Hz), 4.28 (NH, br s, $W_{1/2}$ = 8 Hz), 5.53 (CH_3CHNH, qd, J_{AM} = 3.4 Hz, J_{AX3} = 6.5 Hz), 7.2-8.2 (aromatic, complex multiplet).

Registry No. 1, 3886-69-9; 2, 3886-70-2; 3, 156-34-3; 4, 72984-27-1; 5, 72938-93-3; 6, 72938-94-4; 7a, 72938-95-5; 7b, 72938-96-6; 8a, 72938-97-7; 8b, 72938-98-8; 8c, 72938-99-9; 9a, 72939-00-5; 9b, 72939-01-6; 9c, 72939-02-7; 10a, 72939-03-8; 10b, 72953-41-4; 10c, 72953-42-5; 12, 72939-04-9; $ClSCCl_3$, 594-42-3; 4-chloro-2-methylbenzenesulfenyl chloride, 72939-05-0; 2-nitrobenzenesulfenyl chloride, 7669-54-7; 2,4-dinitrobenzenesulfenyl chloride, 528-76-7.

(12) Kharasch, N.; Langford R. "Organic Syntheses"; Wiley: New York, 1973; Collect. Vol. V, p 474.
(13) Kurzer, F.; Powell, J. R. "Organic Syntheses"; Wiley: New York, 1963; Collect. Vol. IV, p 934.

Stereospecific Transannular Cyclization of (*Z*)- and (*E*)-Thiacyclooct-4-enes: Synthesis and Carbon-13 Nuclear Magnetic Resonance Spectra of Substituted *cis*-1-Thioniabicyclo[3.3.0]octane Salts. Conformational Analysis (Force Field) of (*E*)-Thiacyclooct-4-ene and Its 2- and 3-Methyl Derivatives

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Several substituted (*Z*)- and (*E*)-thiacyclooct-4-enes (1-11) have been synthetized and their acid-promoted transannular cyclizations studied. The reaction appears to be stereospecific: thus the *RR,SS* and *SR,RS* diastereomers of 2-methyl-(*E*)-thiacyclooct-4-ene give, respectively, the *exo*- and *endo*-2-methyl-*cis*-1-thioniabicyclo[3.3.0]octane salts. Similarly, the halogen-promoted (Cl, Br) cyclization of (*Z*)- and (*E*)-thiacyclooct-4-ene gives the *endo*- and the *exo*-4-halogeno derivatives, respectively. Several bridgehead [3.3.0] sulfonium salts have been prepared in this way (12-24) and their ^{13}C NMR spectra compared to those of structurally related systems. Some remarkable shielding effects are reported (a differential ϵ effect amounting to 4 ppm) which allow an insight into the conformational properties of this bicyclic system. Force field computations indicate the twist conformation of (*E*)-thiacyclooct-4-ene is more stable than the chair conformation by 5.06 kcal mol^{-1}. For confirmation of the configurational assignments based on ^{13}C NMR shieldings, the energies of the *RR,SS* and *SR,RS* diastereomers of the 2- and 3-methyl derivatives have also been computed and related to the experimentally determined equilibrium constants.

A distinctive characteristic of medium-size rings (8-11-membered) is their ability to undergo facile transannular reactions, the best known examples being perhaps the hydride shifts accompanying solvolyses.[1] Mesoheterocyclic compounds whose heteroatom possesses marked nucleophilic character display this behavior to the highest degree, strong physical and chemical interactions being established between the heteroatom and electrophilic centers across the ring. As far as S heterocycles are concerned,[2] trans-

(1) (a) Prelog, V.; Traynham, J. G. In "Molecular Rearrangements"; De Mayo, P., Ed.; Interscience: New York, 1964; Vol. 1, p 593. (b) Cope, A. C.; Martin, M. M.; McKervery, M. A. *Q. Rev., Chem. Soc.* **1966**, *20*, 119.

(2) There is evidence that transannular interactions involving sulfide sulfur may already take place in seven-membered rings.[3]

0022-3263/80/1945-2641$01.00/0

Table I. ^{13}C NMR Spectra of Substituted *cis*-1-Thioniabicyclo[3.3.0]octane Salts[a]

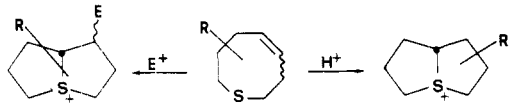
cation	substituent	C_2	C_3	C_4	C_5	C_6	C_7	C_8	CH_3
12[b]	none	45.4	29.3	35.7	66.3				
13[b]	*endo*-2-CH_3	56.5	(36.1)	35.4	66.9	(36.0)	30.9	37.9	13.3
14[b]	*exo*-2-CH_3	60.2	37.5	34.6	66.5	35.6	28.2	44.5	17.3
15[b]	*endo*-3-CH_3	49.5	39.8	42.0	65.9	34.9	26.2	44.8	16.4
16[b]	*exo*-3-CH_3	50.1	37.7	43.2	65.6	36.1	30.2	45.3	17.0
17[b]	3,3-$(CH_3)_2$	54.9	46.7	47.5	65.1	34.6	26.3	44.2	25.5, 25.3
18[b]	5-CH_3	46.1	29.7	42.8	84.0				25.2
19[c]	*endo*-4-OH	40.0	35.3	74.1	65.6	(30.5)	(30.2)	45.7	
20[b]	*exo*-4-OH	42.0	35.5	78.7	73.7	32.7	30.2	45.8	
21[d]	*endo*-4-Br	42.2	36.0	47.2	66.2	33.8	30.5	47.1	
22[d]	*exo*-4-Br	42.7	38.5	53.8	75.8	35.0	30.3	46.0	
23[c]	*endo*-4-Cl	40.9	36.0	59.2	65.6	32.1	30.6	46.7	
24[c]	*exo*-4-Cl	42.0	37.6	65.2	75.4	34.5	30.4	46.1	

[a] In D_2O with dioxane as internal reference. The shieldings (in δ) have been converted to the Me_4Si scale by using $\delta_{dioxane} = 67.18$. [b] Triflate. [c] Chloride. [d] Bromide.

annular interactions were suggested as early as 1954[4] and experimentally confirmed in the subsequent few years. Thus 5-oxothiocane gives physical evidence (IR and dipole moment) of a transannular donor–acceptor interaction between the sulfide and the carbonyl functions and, in addition, under acidic conditions, undergoes a reversible cyclization to a 5-hydroxy-1-thioniabicyclo[3.3.0]octane salt.[5] Similarly, 5-hydroxythiocane undergoes irreversible transannular cyclization upon acid treatment (P_2O_5 followed by picric acid) to give 1-thioniabicyclo[3.3.0]octane picrate.[6]

The recently developed ring enlargement by [2,3] sigmatropic rearrangement of sulfonium ylides[7] provides easy access to homoallylic mesocyclic sulfides (thiacycloalk-4-enes) which are expected to be especially suitable for transannular interaction.[8]

In this paper we report the transannular cyclization of methyl-substituted (*Z*)- and (*E*)-thiacyclooct-4-enes to *cis*-1-thioniabicyclo[3.3.0]octanes under acidic conditions,

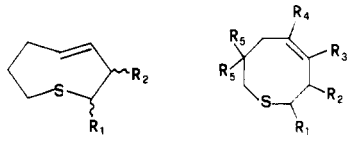


E or Z

focussing in particular on the stereochemical aspects. The cyclization reaction may be made to occur by the action of electrophiles other than the proton, halogen for instance. In this latter case the bicyclic product will carry a substituent at C_4, the stereochemistry of which depends on the configuration of the starting olefin.

Results and Discussion

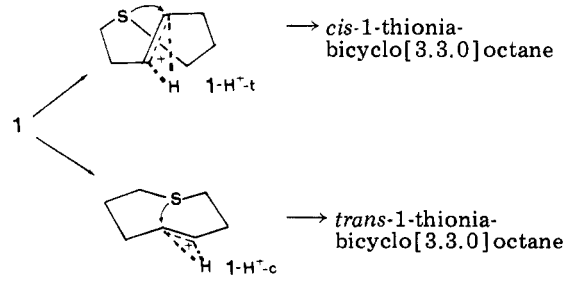
With the exception of the isomeric 4-hydroxy salts, **19** and **20**, which were prepared from thiacyclooctane-*cis*- and -*trans*-4,5-diol, respectively, all the substituted *cis*-1-thioniabicyclo[3.3.0]octane salts were obtained from the appropriate olefin by transannular cyclization. The olefin starting materials are shown as **1–11**, below, while the bicyclic salt products are listed in Table I, where their ^{13}C NMR spectra are also recorded.



1, $R_1 = R_2 = H$
2, $R_1 = CH_3$; $R_2 = H$ (*RR,SS*)
3, $R_1 = CH_3$; $R_2 = H$ (*SR,RS*)
4, $R_1 = H$; $R_2 = CH_3$ (*RS,SR*)
5, $R_1 = H$; $R_2 = CH_3$ (*RR,SS*)
6, $R_1 = R_2 = R_3 = R_4 = R_5 = H$
7, $R_1 = CH_3$; $R_2 = R_3 = R_4 = R_5 = H$
8, $R_2 = CH_3$; $R_1 = R_3 = R_4 = R_5 = H$
9, $R_3 = CH_3$; $R_1 = R_2 = R_4 = R_5 = H$
10, $R_4 = CH_3$; $R_1 = R_2 = R_3 = R_5 = H$
11, $R_1 = R_2 = R_3 = R_4 = H$; $R_5 = CH_3$

Stereospecificity. The parent bicyclic cation, **12**, was obtained as a single product from the *E*, **1**, and the *Z*, **6**, homoallylic sulfide. Since the product arising from the *Z* olefin can only have a cis junction, **12** must necessarily be the *cis*-1-thioniabicyclo[3.3.0]octane salt.

It should be noted that from the *E* homoallylic sulfide **1** either the trans- or the cis-fused bicyclic cation could obtain, depending on whether the protonated intermediate undergoing transannular cyclization has, respectively, the chair, 1-H^+-c, or the twist, 1-H^+-t, conformation. If the

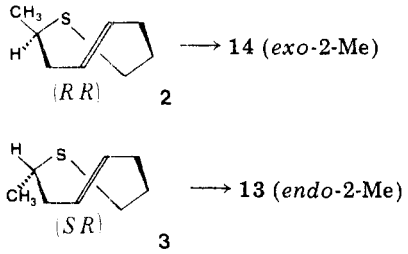


product has the cis geometry it ought to arise from the twist form. However, since the cis-fused bridgehead cation is expected to be considerably more stable than the trans[10,11] and since one does not know whether, once

(3) De Groot, A. E.; Boerma, J. A.; Wynberg, H. *Recl. Trav. Chim. Pays-Bas* **1969**, *88*, 994.
(4) Leonard, N. J.; Fox, R. C.; Oki, M. *J. Am. Chem. Soc.* **1954**, *76*, 5708.
(5) Leonard, N. J.; Milligan, T. W.; Brown, T. L. *J. Am. Chem. Soc.* **1960**, *82*, 4075.
(6) Overberger, C. G.; Lusi, D. *J. Am. Chem. Soc.* **1959**, *81*, 506.
(7) (a) Vedejs, E.; Hagen, J. P. *J. Am. Chem. Soc.* **1975**, *97*, 6878. (b) Ceré, V.; Pollicino, S.; Sandri, E.; Fava, A. *Ibid.* **1978**, *100*, 1516. (c) Vedejs, E.; Hagen, J. P.; Roach, B. L.; Spear, K. *J. Org. Chem.* **1978**, *43*, 1185. (d) Ceré, V.; Paolucci, C.; Pollicino, S.; Sandri, E.; Fava, A. *Ibid.* **1978**, *43*, 4826. (e) Vedejs, E.; Arco, M. J.; Powell, D. W.; Renga, J. M.; Singer, S. P. *Ibid.* **1978**, *43*, 4884.
(8) Very recently a number of reports have appeared on the transannular cyclization of azacyclooct-4-ene and azacyclonon-4-ene promoted by electrophiles.[9]
(9) (a) Wilson, S. R.; Sawicki, R. A. *J. Chem. Soc., Chem. Commun.* **1977**, 431; (b) *J. Org. Chem.* **1979**, *44*, 287, 330.
(10) Eliel, E. L. "Stereochemistry of Carbon Compounds"; McGraw-Hill: New York, **1962**; Chapter 10, pp 273–5.

formed, the latter would not isomerize rapidly, nothing can be inferred from this piece of evidence about the conformer population of the starting olefin **1**. Nevertheless, ^{13}C NMR evidence indicates the twist form of *trans*-thiacyclooct-4-ene to be largely populated[7b] and force field calculations (see below) confirm that the twist is more stable than the chair form by some 5.06 kcal mol^{-1}. It thus appears that the cis cation **12** is both the more stable and the kinetically controlled product.

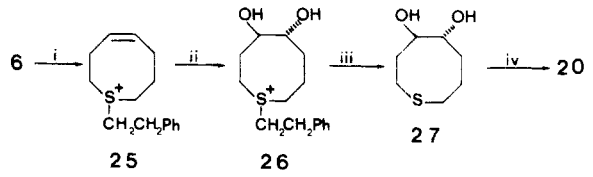
The *endo*- and *exo*-2-methyl derivatives, **13** and **14**, were



obtained separately by cyclization of the individual diastereomers of (*E*)-2-methylthiacyclooct-4-ene.[7b] The ^{13}C NMR shifts leave no doubt of the stereochemical assignment: the Me carbon as well as the carbons α and γ to it (C_2 and C_8) are expected to resonate upfield in the endo with respect to the exo isomer, and on this basis, **13** can be unambigously assigned the endo stereochemistry. The fact that each of the two diastereomeric salts is uniquely obtained from one of the two diastereomeric olefins, while confirming the stereospecificity of the cyclization, also allows unambigous stereochemical correlation between the bicyclic products and their respective precursors. Thus **13** and **14** must arise, respectively, from the *SR,RS*, **3**, and the *SS,RR*, **2**, diastereoisomer of (*E*)-2-methylthiacyclooct-4-ene,[13] as shown. The stereochemical correlation definitely confirms the tentative configurational assignment of **2** and **3** previously proposed on the basis of the ^{13}C NMR shifts of the olefins themselves.[7b] Moreover, the computed (force field; see below) relative stabilities of **2** and **3** are consistent with the experimentally determined equilibrium constant ([**2**]/[**3**] = 6 at 124 °C),[7b] yielding further support to the configurational assignment.

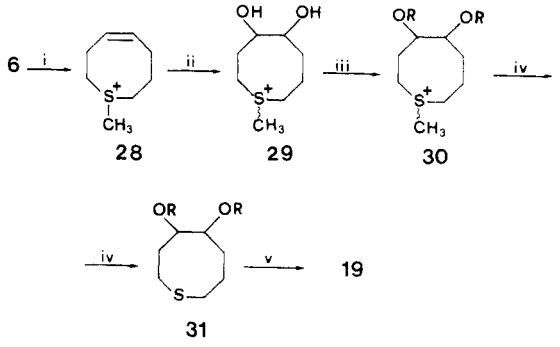
The stereospecificity of the transannular cyclization requires that the *endo*- and *exo*-3-methyl derivatives, **15** and **16**, obtain, respectively, from the *RS,SR* and *RR,SS* isomers of (*E*)-3-methylthiacyclooctene. This was borne out experimentally. On the basis of ^{13}C NMR shifts, the stereochemical assignments of **4** and **5** are straightforward. As models show, the Me group at C_3 is anti to C_5 in the *RS,SR* isomer and gauche to C_5 in the *RR,SS* isomer. Thus in the latter both C_5 and the Me carbon are expected to be upfield with respect to the former. Indeed, in **5** the CH_3 and C_5 shieldings are upfield by, respectively, 4.9 and 4.1 ppm with respect to those of **4**. The latter is then assigned the *RS,SR* configuration and the former the *RR,SS* configuration. The assignment is in accord with the relative stability of **4** and **5**. A study of the **4** ⇌ **5** equilibration (see Experimental Section) established that, at equilibrium

Scheme I[a]



[a] (i) $PhCH_2CH_2I$, $AgBF_4$, CH_2Cl_2; (ii) 30% H_2O_2, AcOH; (iii) MeONa, MeOH, reflux; (iv) CF_3SO_3H.

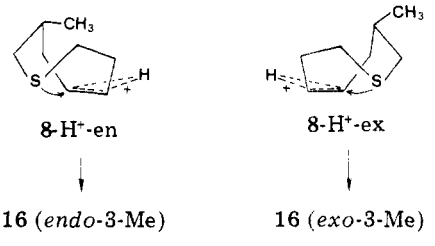
Scheme II[a]



[a] R = Tetrahydropyranyl; (i) $CF_3SO_3CH_3$, CH_2Cl_2; (ii) 30% H_2O_2, OsO_4, 2,3-dihydropyran, H^+; (iv) $LiAlH_4$, THF; (v) HCl.

at 120 °C, [**4**]/[**5**] = 3.6. On the other hand, force field calculations (see below) indicate that the *RS,SR* diastereoisomer is more stable than the *RR,SS*.

The transannular cyclization of the *Z* homoallylic sulfides **7** and **8** gave a remarkable result. While from **7** nearly equal amounts of **13** and **14** were obtained, from **8** the exo cation **16** was obtained exclusively. This finding, surprising at first sight, becomes completely reasonable when the diastereomeric protonated cis olefins 8-H$^+$-en and 8-H$^+$-ex



are considered. It is immediately apparent that the C_3–Me group projects "outside" in 8-H$^+$-ex and "inside" in 8-H$^+$-en, where it is engaged in a strong 1,4 repulsive interaction with one of the C_8 H's. Since no endo product (<2%) is formed in the cyclization of **8**, the energy of 8-H$^+$-en must be higher by at least 2.5 kcal mol^{-1}, which is quite reasonable in view of the interaction involved. Models show that in the case of **7** no such strong conformational bias is present in the diastereomers of protonated **7**, which justifies the formation of both diastereomeric cations **13** and **14**.

Of the isomeric 4-hydroxy salts, the exo salt, **20**, was obtained by acid-promoted cyclization of thiacyclooctane-*trans*-4,5-diol (**27**), prepared through the sequence outlined in Scheme I, the relevant feature of which is the protection of the sulfide function by alkylation with the 2-phenylethyl group, subsequently removed by methoxide-catalyzed β-elimination of styrene.

The *endo*-4-hydroxy derivative, **19**, was obtained from the cis 4,5-diol (not isolated, however) as outlined in Scheme II. This procedure is similar to that used in previous work[10] insofar as protection of sulfide was achieved by methylation and deprotection by $LiAlH_4$ re-

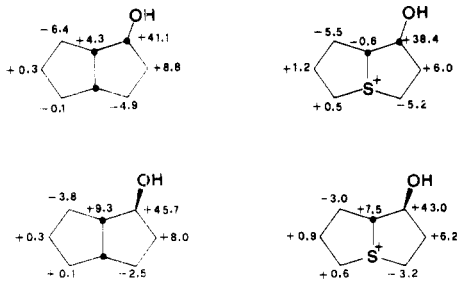
(11) Prolonged heating of **12** (PF_6^-) at temperatures which are known to cause pyramidal inversion of sulfonium sulfur[13] failed to produce detectable isomerization of **12**, indicating the latter is the thermodynamically stable isomer (by at least 2.5 kcal mol^{-1}).

(12) (a) Garbesi, A.; Corsi, N.; Fava, A. *Helv. Chim. Acta* **1970**, *53*, 1499. (b) Barbarella, G.; Garbesi, A.; Boicelli, A.; Fava, A. *J. Am. Chem. Soc.* **1973**, *95*, 8051 and references therein.

(13) In each pair of configurational descriptors, the first descriptor refers to the chiral center and the second to the chiral plane. This convention will be used throughout this paper.

(14) Ceré, V.; Guenzi, A.; Pollicino, S.; Sandri, E.; Fava, A. *J. Org. Chem.* **1980**, *45*, 261.

Chart I

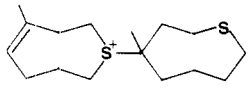


duction. Unless the hydroxyl groups were suitably protected, however, the reduction step was found to cause extensive ring opening to an unsaturated methyl sulfide.

The isomeric 4-bromo and 4-chloro compounds, endo (**21** and **23**) and exo (**22** and **24**), were obtained by bromine- and chlorine-promoted stereospecific cyclization of the cis, **6**, and trans, **1**, parent olefin, respectively. The ^{13}C spectra (Table I) leave no doubt about the stereochemical assignment, the major distinctive feature being the relatively greater shielding effect on C_6 and C_2 by the endo 4-substituents (γ effects).

The bicyclic salts **17** and **18** were obtained from the corresponding olefins **10** and **11**, respectively. Of course, no isomeric products could be formed in these instances.

Prominently missing from Table I are the isomeric 4-methyl-substituted bicyclic salts. These were expected to be obtained from (*Z*)-4-methylthiacyclooct-4-ene (**9**); however, acid treatment failed to cause transannular cyclization of **9**, which gave instead, as the major outlet, an intermolecular reaction product, **32**. Evidently in the

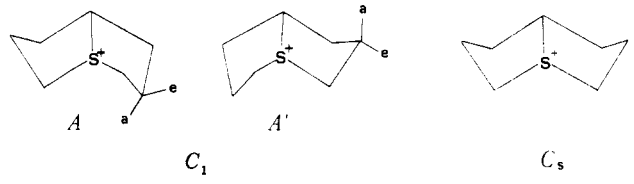


32

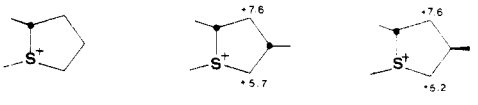
protonated olefin, **9**-H^+, the positive charge resides mainly on the tertiary carbon, C_4, and intramolecular cyclization at C_5 is slow enough to permit capture by another sulfide molecule at the tertiary carbonium ion center. Thus the 4-methylthiacyclooct-4-ene route is not a viable one for obtaining the 4-methyl derivatives.

Carbon-13 Shieldings. Several regularities emerge from the data in Table I and warrant a comparison with structurally similar systems such as the corresponding carbocycle derivatives[15] on one side and monocyclic thiolanium cations on the other.[16] As expected,[17] substituent effects involving carbon atoms remote from the heteroatom are approximately the same as those in the carbocyclic system, while those involving carbon atoms adjacent to the heteroatom tend to differ considerably. A particularly illustrative example is offered by the 4-hydroxy compounds, shown in Chart I in the form of shift differences from the respective parent compound. There appears to be a close match between the corresponding carbons in the horizontal pairs, with one exception, however. The exception is the β-effects at the bridgehead carbon, which tend to be less deshielded in the heterocycle than in the carbocycle. Actually, for the endo isomer the β-effect is essentially nil, if not slightly shielding (–0.6), and this appears to be a distinctive feature of these bicyclic salts as it occurs also in the *endo*-4-Br (**21**, –0.1) and *endo*-4-Cl (**23**, –0.7) compounds. The known tendency of β effects to be less deshielding for carbons adjacent to the heteroatom than for carbons remote from the heteroatom[17] can be also appreciated by the comparison of the C_2 and C_4 shieldings in **15**, **16**, and **17**. On the other hand, the unusually large α effect[17] at carbons directly bound to the heteroatom can be seen from the shielding of the substituent-bearing carbons in **13**, **14**, and **18**.

Perusal of the data in Table I evinces another remarkable fact, namely, a very large differential shielding of C_7 in the endo–exo pair **15**–**16**, $\Delta\delta$ = 4.0 ppm. This value is unquestionably too high for a differential ϵ effect and can only arise from some conformational change occurring at the unsubstituted ring when the other ring is substituted at C_3 either on the endo or on the exo side. This is not unreasonable since C_7, being at the tip of the envelope flap, is the only carbon of its ring which can undergo a major conformational change, being set either above or below the median plane defined by the other four atoms. The bicyclic parent ion **12** can conceivably adopt either the C_1 or the C_5 conformation, or both.[18] If the C_1 form is assumed to be largely populated, it may be easily seen that since the 3-Me group will, in either case, tend to assume the quasi-equatorial (e) orientation, the *exo*- and the *endo*-3-Me isomer would populate conformation A (C_7 up) and A′ (C_7 down), respectively. In the latter conformation,



C_7 is gauche to both C_4 and C_2 while in the former it is approximately anti to the same carbons. Henceforth, C_7, C_4, and C_2 would all be expected to be upfield in the endo isomer (conformation A′) with respect to the exo isomer (conformation A), precisely as found: $\Delta\delta_{C_7}$ = –4.0 ppm, $\Delta\delta_{C_2}$ = –0.6 ppm, and $\Delta\delta_{C_4}$ = –1.2 ppm. The shielding differences are not large (however, the puckering of five-membered rings being relatively small, they cannot be very large anyway) but have the correct relative magnitude and sign and therefore can be considered significant. If these ideas are correct, they ought to find verification in the C_7 shielding value of the 3,3-dimethyl compound, **17**. Because of the *gem*-dimethyl substitution at C_3, **17** must adopt conformation A′; hence, C_7 should have the same conformational setting as that in **15** and approximately the same shielding. This turns out to be precisely the case, as shown by the data in Table I. Further support for the idea that these shielding effects arise from the conformational setting of C_7 comes from data pertaining to monocyclic thiolanium salts.[16] *cis*-1,2-Dimethylthiolanium may be considered as a *cis*-1-thioniabicyclo[3.3.0]octane from which C_7 has been chopped off. The β-effects of a 4-Me substituent, either cis or trans to the other two methyls are as shown.



The effects at corresponding carbons appear to be very close in the two isomers and close in turn to those observed

(15) Whitesell, I. K.; Matthews, R. S. *J. Org. Chem.* **1977**, *42*, 3878.
(16) Barbarella, G.; Dembech, P., to be submitted for publication. We thank the authors for letting us know of their results before publication.
(17) Barbarella, G.; Dembech, P.; Garbesi, A.; Fava, A. *Org. Magn. Reson.* **1976**, *8*, 469. Willer, R. L.; Eliel, E. L. *Ibid.* **1977**, *9*, 285. Eliel, E. L.; Rao, V. S.; Riddell, F. G. *J. Am. Chem. Soc.* **1976**, *98*, 3583. Arai, K.; Kukunaga, M.; Iwamura, H.; Oki, M. *Tetrahedron Lett.* **1976**, 1685.
(18) Force field calculations indicate that in bicyclo[3.3.0]octane these two types of conformations have about the same energy; hence that which corresponds to our C_2 is about twice as populated.[19]
(19) Allinger, N. L.; Tribble, M. Thomas; Miller, M. A.; Wertz, D. H. *J. Am. Chem. Soc.* **1971**, *93*, 1637.

Table II. Total Energy, Energy Components, and Structural Data for Chair and Twist Forms of (E)-Thiacyclooct-4-ene

	chair	twist	energy difference
total energy, kcal mol^{-1}	22.49	17.43	5.06
bond stretching, kcal mol^{-1}	0.90	0.84	0.06
angle bending, kcal mol^{-1}	5.54	4.54	1.00
stretch-bend, kcal mol^{-1}	0.3	0.23	0.09
torsion, kcal mol^{-1}	8.89	5.68	3.21
1,4 van der Waals, kcal mol^{-1}	7.35	6.11	1.24
nonbonding, kcal mol^{-1}	−0.51	0.03	−0.54
C-S-C, deg	103.3	103.9	
ω^a (C_3-C_4-C_5-C_6), deg	140.8	141.7	
ω^a (S-C_2-C_3-C_4), deg	25.6	52.1	
ω^a (C_5-C_6-C_7-C_8), deg	12.4	41.7	

[a] Dihedral angle about the central bond.

in the bicyclic system in the *exo*-3-Me compound, **16** (7.5 and 4.7). This indicates that in **16** the C_7 bridge is anti to C_2 and C_4 which requires the envelope flap to be "upward" in the unsubstituted ring.

Force Field Computations

The force field method is known to provide a powerful entry into understanding the structure and energy of a wide range of organic molecules.[20] We have therefore applied it to obtain information about the energy and geometry of the two possible conformations, the twist and distorted chair, of (*E*)-thiacyclooct-4-ene (**1**) as well as the *RR,SS* and *RS,SR* diastereomers (twist conformation only) of the 2-methyl (**2** and **3**) and 3-methyl (**5** and **4**) derivatives of **1**. This information was deemed necessary to definitely confirm the conformational and configurational assignments based on ^{13}C NMR (see above and ref 7b).

The force field parameters employed were those tabulated by Allinger and co-workers for alkanes,[21a] alkenes,[21b,c] and thiaalkanes.[21d] For energy optimization the steepest descent method described by Schleyer[22] was adopted, with 0.002 kcal mol^{-1} as the threshold for energy convergence and 0.001 Å as the maximum final displacement in Cartesian coordinates. The starting conformation was set up from natural bond lengths and angles, while torsional angles were estimated from Dreiding models and varied until ring closure was obtained. For the methyl derivatives, the optimized geometry of the parent compound was used as the starting point.

The computed total energies and the energy components for the twist and chair conformations of **1** are reported in Table II, along with some of their more remarkable structural features. As shown, the twist conformation turns out to be more stable by some 5 kcal mol^{-1} which definitely confirms the previous tentative conformational assignment.[7b] For an understanding of the origin of the greater strain of the chair conformer, it is useful to compare the strain-energy components of the two forms (Table II). The main factors appear to be, in order, torsional, van der Waals, and angle-bending strains. A look at the geometrical parameters allows one to see that these terms operate the way they do because the torsion angle at the bonds joining the two "sides" of the molecule (C_2–C_3 and C_6–C_7) is relatively very small in the chair form. Indeed, an analysis of the data shows most of the energy difference (81% of the torsional and 91% of the van der Waals strain) arises from interactions involving atoms attached at the C_2–C_3 and C_6–C_7 segments. The energy difference between chair and twist forms, about twice as large in the heterocyclic as in the carbocyclic olefin (5.06 vs. 2.43[21c] or 3.14[21e] kcal mol^{-1}), may be qualitatively rationalized in similar terms. In fact, the calculated[21e] torsion angles at the bonds joining the two "sides" of the *trans*-cyclooctene molecule (C_3–C_4) are 50 and 42.4° in the twist and chair conformer, respectively; i.e., they differ much less than they do in thiacyclooct-4-ene.

Of the other geometrical features, the double bond torsional angle (141.7°) is worth noting. Although this value differs considerably from that computed by Allinger for *trans*-cyclooctene (149°;[21] however, an older set of force field parameters was used in this calculation), it is close to the value computed by Ermer (138°)[21e] which is, in turn, very close to the experimental value (137.7[23a] and 136°[23b]). The close resemblance between the carbocyclic and the heterocyclic olefin is indicative that the two systems are about equally strained.

The strain energy computations of the diastereomeric 2- and 3-methyl derivatives of (*E*)-thiacyclooct-4-ene have provided answers consistent with the experimentally determined diastereomer populations. Thus the *RR,SS* 2-methyl derivative, **2**, has been computed to be more stable by 0.94 kcal mol^{-1}. This value may be compared to an equilibrium constant [**2**]/[**3**] = 6 at 124 °C [ΔG = 1.4 kcal mol^{-1}).[7b] Similarly, for the 3-methyl derivatives, the force field computations indicate the *RS,SR* diastereomer, **4**, to be more stable by 1.58 kcal mol^{-1}; the experimental value of the equilibrium constant is [**4**]/[**5**] = 3.6 at 120 (ΔG = 1.0 kcal mol^{-1}). Assuming, which is reasonable, that the entropy contribution is minor, one sees that the agreement between calculated and experimental energy differences is satisfactory and lends further support to the stereochemical assignments.

A detailed analysis (see the Supplementary Material) of the energy contributions shows that the major factor responsible for the energy difference within a pair of diastereomers is the nonbonding interaction between the Me group and an H atom at the γ ring carbon, which is gauche in one diastereomer and anti in the other (see structures above). It is precisely the same steric interaction which had been postulated to be responsible for the ^{13}C shieldings of the atoms involved (γ effects) and used for the tentative configurational assignments.[7b]

Experimental Section

Proton NMR spectra were recorded at 60 MHz on a JEOL C-60 HL instrument and at 100 MHz on a Varian XL-100 operating in the CW mode. Proton noise decoupled ^{13}C spectra were recorded at 25.15 MHz with a Varian XL-100 by the FT technique; single-frequency off-resonance spectra were obtained by irradiation at δ −4 in the proton spectrum. Unless otherwise stated, ^1H and ^{13}C shifts are given in parts per million from Me_4Si in $CDCl_3$ solvent. GLC analyses were carried out with a Hewlett-Packard 5700 instrument equipped with a flame-ionization detector ($^1/_8$ in. × 3 m column, 10% XE-60 on Chromosorb W). Preparative

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(21) (a) Wertz, D. H.; Allinger, N. L. *Tetrahedron* **1974**, *30*, 1579. (b) Allinger, N. L.; Sprague, J. T. *Ibid.* **1975**, *31*, 21. (c) Allinger, N. L.; Sprague, J. T. *J. Am. Chem. Soc.* **1972**, *94*, 5734. (d) Allinger, N. L.; Hickey, M. J. *Ibid.* **1975**, *97*, 5167. (e) Ermer, O.; Lifson, S. *Ibid.* **1973**, *95*, 4121.

(22) Williams, J. E.; Stang, P. J.; Schleyer, P. R. *Annu. Rev. Phys. Chem.* **1968**, *19*, 531.

(23) (a) Ermer, O. *Angew. Chem., Int. Ed. Engl.* **1974**, *13*, 604. (b) Traettenberg, M. *Acta Chem. Scand., Ser. B* **1975**, *29*, 29.

GLC separations were carried out with a Varian Aerograph 712 instrument ($^3/_8$ in. × 3 m column, 10% XE-60 on Chromosorb W, 60–80 mesh).

Solvents and reagents were obtained dry as follows. Methylene chloride, *tert*-butyl alcohol, and diisopropylamine were distilled from calcium hydride, and ethyl ether was distilled from $LiAlH_4$. Tetrahydrofuran, dried over sodium and distilled, was redistilled from $LiAlH_4$ immediately before use. Dimethylformamide was dried over molecular sieves (Union Carbide, type A 4) for 48 h. All reactions involving organolithium reagents were carried out under nitrogen, the reagents being introduced by syringe through a rubber stopper.

The cyclic homoallylic sulfides **2–11** were all synthetized by the same general method, i.e., ring expansion of the appropriate 2-vinylthiolanium methylides via [2,3] sigmatropic rearrangement.[7a,d] The 2-vinylthiolanium salt precursors for ring expansion were obtained by methylation ($CF_3SO_3CH_3$) of the appropriate thiolane derivative, prepared by lithium diisopropylamide cyclization of substituted allyl 3-halopropyl sulfides.[7c] The latter, in turn, were obtained by the reaction of the suitably substituted thietanes with allylic bromides.[24,7c]

3-Bromopropyl crotyl sulfide (33) was prepared by heating neat thietane (7.4 g, 0.1 mol) with commercial crotyl bromide (13.5 g, 0.1 mol) at 50 °C for 24 h. Distillation of the reaction mixture gave the title compound: 17 g (81%); bp 93–94 °C (2 mm). The material is comprised of two products (GLC, 7:1 ratio), most likely *E*/*Z* isomers (see below). In the ^1H NMR, however, only the methyl resonance shows up as two doublets: δ 1.67 and 1.71 (major, J = 6.0 Hz; from the other resonances the presence of the minor isomer cannot be determined), 5.5 (m, 2 H, olefinic protons), 3.52 (t, 2 H, CH_2Br), 3.10 (d, 2 H, $=CHCH_2S$), 2.60 (t, 2 H, CH_2CH_2S), 2.08 (quintet, 2 H, $CH_2CH_2CH_2$). Anal. Calcd for $C_7H_{13}SBr$: C, 40.20; H, 6.27. Found: C, 40.31; H, 6.15.

Allyl 3-bromo-2,2-dimethylpropyl sulfide (34) was obtained (85%) by the same procedure as outlined for **33** from 3,3-dimethylthietane[25] and allyl bromide: bp 95–96 °C (5 mm); ^1H NMR δ 5.8 (m extending over 0.6 ppm, 1 H, =CH), 5.1 (m extending over 0.4 ppm, 2 H, $=CH_2$), 3.60 (s, 2 H, CH_2Br), 3.17 (d, J = 6.0 Hz, 2 H, $=CHCH_2S$), 2.54 (s, 2 H, $C(CH_3)_2CH_2S$), 1.10 (s, 6 H, CH_3). Anal. Calcd for $C_8H_{15}SBr$: C, 43.05; H, 6.78. Found: C, 42.96; H, 6.85.

3-Chloropropyl 2-Methylallyl Sulfide (35). Thietane (7.4 g, 0.1 mol) and 2-methylallyl chloride (15 g, 0.165 mol) were heated at 95 °C for 48 h. Distillation of the reaction mixture gave the title compound: 7.0 g (42.5%); bp 80–83 °C (3 mm) [lit.[24] 48 °C (0.05 mm)]; ^1H NMR δ 4.82 (br s, 2 H, $=CH_2$), 3.81 (t, 2 H, CH_2Cl), 3.11 (s, 2 H, $=CCH_2S$), 2.55 (t, 2 H, CH_2CH_2S), 1.98 (quintet superimposed on a singlet at 1.82, 5 H overall, $CH_2CH_2CH_2$ and CH_3). Anal. Calcd for $C_7H_{13}SCl$: C, 51.05; H, 7.96. Found: C, 51.14; H, 7.89.

Longer reaction times (64 h) resulted in better conversion (70%) but caused significant isomerization of the methylallyl derivative, probably to the 2-methylpropen-1-yl derivative. On the other hand, at the lower temperature (50 °C) recommended by the published procedure,[24] mainly unreacted starting material was recovered.

2-(1-Propen-1-yl)thiolane (36). 3-Bromopropyl crotyl sulfide (**33**; 6.27 g, 0.03 mol) was added dropwise with stirring to a THF solution of lithium diisopropylamide at −78 °C [prepared from diisopropylamine in THF (3.34 g, 0.033 mol in 50 mL) and 1 equiv of butyllithium in hexane (1.6 M)]. After being allowed to stand 1 h at −78 °C, the mixture was quenched with H_2O, brought to room temperature, acidified with dilute HCl, and extracted with CH_2Cl_2. The extracts were washed with water, dried over $CaSO_4$, and evaporated. The residue was distilled at reduced pressure to give **36**: 3.0 g (76%); bp 73–74 °C (12 mm). GLC shows the presence of the minor geometrical isomer which, however, does not show up in the ^1H NMR [δ 5.50 (m, 2 H, olefinic protons), 3.90 (m, 1 H, α-CH), 2.90 (m, 2 H, α-CH_2), 2.2–1.4 (m partially superimposed on a doublet at 1.63, 7 H overall, β-CH_2's and CH_3)]. In the ^{13}C spectrum the minor component (~1:6) shows up clearly and may be definitely identified as the *Z* isomer. The ^{13}C shifts (δ) of the minor isomer are given in parentheses: $CH_3CH=$, 133.1 (132.6); $>CHCH=$, 125.5 (124.5); C_2, 50.9 (44.5); C_3, 38.3 (38.3); C_5, 33.0 (32.8); C_4, 30.8 (31.0); CH_3, 17.5 (13.0). Anal. Calcd for $C_7H_{12}S$: C, 65.56; H, 9.43. Found: C, 65.61; H, 9.45.

4,4-Dimethyl-2-vinylthiolane (37) was obtained in 70% yield by the procedure outlined for **36** from allyl 3-bromo-2,2-dimethylpropyl sulfide (**34**); bp 52 °C (5 mm). The ^1H NMR spectrum can be interpreted as first order and shows that the conformation of the molecule is essentially fixed. The relevant feature is an AB quartet at δ 2.70 (2 H, J = 10.5, $\Delta\nu$ = 35.0 Hz, α-CH_2), the high-field part of which is further split by a small (~0.5 Hz) long-range coupling. This small coupling is also present in a quartet (1.95, 1 H, J = 13.0 and 6.3 Hz) which appears to be the B part of a ABMX four-spin system. The proton concerned must be one of the H's at C_3, and its long-range coupling to one of the H's at C_5 indicates that these protons are in a W arrangement and must therefore be quasi-equatorial. The A part of the four-spin system, δ 1.55, is also a quartet (J = 13.0 and 10.8 Hz). The first is the geminal coupling and the second must be a trans diaxial coupling with the methyne proton at C_2. Indeed, this latter proton shows up as an octet (δ 4.02, J = 10.8, 8.6, and 6.3 Hz). Clearly the 8.6-Hz coupling is the coupling with the olefinic C–H. The spectrum is completed by the characteristic terminal vinyl absorption (δ 6.2–4.8, 3 H) and by two singlets, δ 1.15 and 1.12 (3 H each), due to unequivalent methyls. The spectrum is consistent with a half-chair ring conformation (maximum staggering at C_3–C_4),[26] with the vinyl and the cis-methyl groups occupying quasi-equatorial positions. Anal. Calcd for $C_8H_{14}S$: C, 67.54; H, 9.92. Found: C, 67.48; H, 9.88.

2-(2-Propenyl)thiolane (38) was prepared from 3-chloropropyl 2-methylallyl sulfide (**35**) by the procedure outlined for **36**, except that the reaction time was increased to 3 h. The crude product was purified by distillation: yield 65%; bp 182 °C (758 mm). In the ^1H NMR spectrum (100 MHz) the olefinic protons (δ 4.85, 2 H) give rise to an AB pattern ($\Delta\nu$ = 20.5 Hz, J = 1.6 Hz), the high-field part of which shows a long-range coupling to the CH_3 protons. The latter appear as a doublet (δ 1.83, J = 1.4 Hz, 3 H). Other resonances are as follows: δ 3.98 (t, J = 6.3 Hz, 1 H, α-CH), 2.88 (m, 2 H, α-CH_2), 2.2–1.6 (complex m superimposed on the CH_3 doublet, 7 H overall, β-CH_2 and CH_3); ^{13}C NMR δ 145.3 (>C=), 111.7 ($=CH_2$), 54.8 (C_2), 35.7 (C_3), 32.9 (C_5), 31.1 (C_4), 19.2 (CH_3). Anal. Calcd for $C_7H_{12}S$: C, 65.56; H, 9.43. Found: C, 65.48; H, 9.47.

1-Methyl-2-(1-propenyl)thiolanium hexafluorophosphate (39) was prepared[7d] from 2-(1-propenyl)thiolane (**36**; 2.56 g, 0.02 mol) followed by metathesis with ammonium hexafluorophosphate. Extraction with CH_2Cl_2 gave 5.3 g (92%) of a viscous uncrystallizable material. Its ^1H NMR is consistent with the title compound, all four possible isomers of which appear to be present. Their relative abundance, estimated from the intensities of their SCH_3 singlets, is roughly 1:1.5:4:8. From the known distribution of the *E*/*Z* geometrical isomers of the starting material (**36**), it follows that in the two more abundant isomers the double bond has the *E* configuration. Moreover, from the SCH_3 shifts it may be inferred that the more abundant isomer of the *Z* as well as of the *E* pairs has a trans arrangement of the SCH_3 and the propenyl group.[7b,27] These assignments are fully confirmed by the ^{13}C NMR shieldings. The propenyl carbon shifts (C_2 and C_1) in the four isomers (in order of increasing abundance) are as follows: δ 137.7 and 119.7, 134.0 and 123.9, 138.4 and 120.3, 135.1 and 124.6. These data identify the four isomers as the *Z*-cis, *Z*-trans, *E*-cis, and *E*-trans, respectively. In fact, corresponding carbons are consistently upfield (0.6–1.1 ppm) in the minor pair (*Z* double bond), and, within each pair, C_1 is upfield by 4.2 or 4.7 ppm (γ effect) in the isomer which, on the basis of the SCH_3 shift criterion, may be assigned the cis configuration.[7d,27] Anal. Calcd for $C_8H_{15}SPF_6$: C, 33.34; H, 5.24. Found: C, 33.26; H, 5.28.

1,4,4-Trimethyl-2-vinylthiolanium hexafluorophosphate (40) was prepared as described for **39** from 4,4-dimethyl-2-vinylthiolane (**37**). The crude salt was a crystalline material, (mp 60–80 °C) which from the ^1H NMR appears to comprise two

(24) Esclamadon, C. German Patent 1 925 697, Nov 27, 1969; *Chem. Abstr.* **1970**, *72*, 42785.
(25) Searles, S., Jr.; Lutz, E. F. *J. Am. Chem. Soc.* **1958**, *80*, 3168.
(26) Barbarella, G.; Garbesi, A.; Fava, A. *J. Am. Chem. Soc.* **1975**, *97*, 5883.
(27) Cerè, V.; Paolucci, C.; Pollicino, S.; Sandri, E.; Fava, A. *J. Org. Chem.* **1979**, *44*, 4128.

isomers in an ~1.3:1 ratio, characterized by SCH_3 singlets at δ 2.90 and 3.25, respectively. This differential shielding permits assignment of the cis structure to the more abundant isomer. Crystallization from EtOH yielded the more abundant cis isomer: mp 113–114 °C; ^1H NMR (100 MHz, acetone-d_6) δ 6.22–5.64 (m, 3 H, vinyl H's), 5.19 (m, 1 H, α-CH), 3.60 (AB q, J = 13.0 Hz, $\Delta\nu$ = 50 Hz, α-CH_2), 2.90 (s, 3 H, SCH_3), 2.42 (m, 2 H, β-CH_2; by irradiation at 5.2, an AB q is obtained, J = 14.0 Hz, $\Delta\nu$ = 21.5 Hz), 1.23 and 1.39 (2 s, 3 H each, β-CH_3's); ^{13}C NMR (acetone-d_6; in parentheses are the shifts of the minor trans isomer, measured on the mixture) CH=, δ 128.3 (132.0), $=CH_2$, 126.0 (123.0), C_2, 59.6 (66.8), C_5, 57.2 (55.2), C_3, 45.7 (48.6), C_4, 44.4 (45.4), SCH_3, 21.3 (27.0), $(CH_3)_2$, 27.2 and 26.7 (27.4 and 28.0). Anal. Calcd for $C_9H_{17}SPF_6$: C, 35.76; H, 5.67. Found: C, 35.67; H, 5.59.

1-Methyl-2-(2-propenyl)thiolanium hexafluorophosphate (41) was prepared (85%) from 2-(2-propenyl)thiolane (**38**) as described for **39**. The salt was a viscous uncrystallizable material. Its ^1H and ^{13}C NMR spectra showed the trans and cis isomers to be present in the ratio of ~4:1, the major and the minor isomers having their SCH_3 resonances at δ 3.02 and 2.65, respectively. The configurational assignment is confirmed by the ^{13}C shieldings (minor isomer in parentheses): CH=, δ 138.9 (135.4); $=CH_2$, 118.3 (120.3); C_2, 72.2 (66.3); C_5, 45.3 (46.1); C_3, 34.6; C_4, 28.7; SCH_3, 25.9 (23.4); CCH_3, 20.2 (20.3). The C_3 and C_4 resonances of the minor isomer could not be identified and are probably hidden below the seven-line pattern of acetone-d_6. Anal. Calcd for $C_8H_{15}SPF_6$: C, 33.34; H, 5.24. Found: C, 33.31; H, 5.28.

(*Z*)-Thiacyclooct-4-ene (6),[7d] (*Z*)-2-methylthiacyclooct-4-ene[7b] (7), and (*Z*)-5-methylthiacyclooct-4-ene[27] (11) have been previously described.

(*E*)-Thiacyclooct-4-ene (1) was prepared by stereospecific olefin inversion of the *Z* isomer, **6**, as previously described.[14]

(*RR,SS*)-(*E*)-2-Methylthiacyclooct-4-ene (2)[7b] and the *SR,RS* diastereomer, **3**,[7b] were obtained from mixtures which had been preliminarily enriched in **2** or **3** according to the procedure described below, which exploits a rate differential for formation of the $HgCl_2$ adducts with the *E* and *Z* homoallylic sulfides. One gram of crude 2-methylthiacyclooct-4-ene (**7**/**2**/**3** ratio of 41:7:52)[7b] in 40 mL of pentane was briefly shaken with aqueous $HgCl_2$ (60 mL, 6% w/v). The mercuric chloride adduct was filtered as rapidly as possible, treated with aqueous KI to regenerate the sulfides, and extracted with pentane. Evaporation of solvent left a residue (0.5 g) of composition 15:15:70 **7**/**2**/**3**, from which **3** was obtained (~95% pure) by preparative GLC.[7d] Similarly, for the isolation of **2**, 2,6-di-*tert*-butylphenol (0.3 g) was added to 1 g of crude sulfide[7b] in 40 mL of *n*-octane, and the solution was heated at 125 °C for 2 h in order to establish the **2** ⇌ **3** equilibrium.[7b] The mixture was then enriched by the above $HgCl_2$ method to give 0.4 g of a sulfide of composition 10:75:15 **7**/**2**/**3**, from which **2** was obtained (~92% pure) by preparative GLC. From the filtrates of the $HgCl_2$ treatments a solid separated out, from which a sulfide was recovered which consisted mainly of the cis isomer **7**.

(*Z*)-3-Methylthiacyclooct-4-ene (8) was prepared by essentially the same ring-expansion procedure previously applied to the synthesis of the 2-methyl derivatives.[7d] The mixture of 1-methyl-2-(1-propenyl)thiolanium hexafluorophosphate isomers (**39**; 2.88 g, 0.01 mol) was treated with *t*-BuOK (1.44 g, 0.013 mol) to give 1.2 g (85%) of crude sulfide which by GLC appeared to be made up of three products in the ratio 70:15:15, all characterized by the same molecular ion (*m/e* 142) and mass spectra. GLC monitoring showed the two minor products to be gradually and completely converted into the third major product by heating at 150 °C. The direction of the change suggests that the latter is the *Z* isomer, bp 199 °C (756 mm). The ^1H NMR is very complex even at high field (270 MHz), and few resonances can be assigned. However, the *Z* configuration of the double bond is confirmed: δ 5.45 and 5.35 (2 m, 1 H each, olefinic protons), 2.79 (m, 3 H overall, one of which must be C_3–H; see below), 2.59, 2.51, 2.27, and 1.99 (4 m, 1 H each), 1.74 (m, 2 H), 1.06 (d, J = 6.2 Hz, 3 H, CH_3). Irradiation at δ 2.8 changes the δ 5.35 multiplet into a doublet (part of an AB q, J = 10.5 Hz, cis double bond). The δ 5.35 multiplet appears likely to pertain to C_4–H: ^{13}C NMR δ 136.9 (C_4), 128.4 (C_5), 41.1 (C_2), 36.3 (C_3), 31.1 (C_8), 30.9 (C_7), 24.5 (C_6), 22.3 (CH_3). Anal. Calcd for $C_8H_{14}S$: C, 67.54; H, 9.92. Found: C, 67.62; H, 9.87.

(*RS,SR*)- and (*RR,SS*)-(*E*)-3-Methylthiacyclooct-4-ene (4 and 5). The crude sulfide mixture arising by ring expansion of the 2-(1-propenyl)thiolanium methylide from **32** (see above) was enriched in the trans isomers by selective formation of the mercuric chloride adducts (see the section for the separation of **2** and **3** above). From 2.5 g of crude sulfide of composition 70:15:15 **8**/**4**/**5**, 1 g of sulfide was obtained of composition 30:40:30 **8**/**4**/**5**, from which the products of intermediate, **4**, and longest retention time, **5**, were separated by preparative GLC at 115 °C. The two diastereomers have the following ^{13}C NMR (the numbers in parentheses pertain to diastereomer **5**): C_4, δ 135.6 (135.4); C_5, 136.0 (131.9); C_2, 50.6 (50.2); C_3, 43.7 (43.6); C_6, C_7, and C_8, 37.9, 35.0, and 34.9, interchangeable (37.8, 36.5, and 35.1, interchangeable); CH_3, 18.8 (13.9). On the basis of these shieldings (see Results and Discussion section), **4** and **5** are assigned the title configurations.

While in the absence of a radical inhibitor both **4** and **5** are irreversibly converted into the cis olefin **8**, in the presence of 2,6-di-*tert*-butylphenol such isomerization is almost completely suppressed, and the interconversion of **4** and **5** may be observed. A few sample points have established the rate of equilibration at 120 °C to be on the order of 6×10^{-5} s^{-1}, which is within a factor of 2 of that measured for the interconversion of (*RR,SS*) and (*RS,SR*) diastereomers of (*E*)-2-methylthiacyclooct-4-ene.[7d] The equilibrium constant, which may be reached from either side, was found to be [**4**]/[**5**] = 3.6 at 120 °C.

(*Z*)-4-Methylthiacyclooct-4-ene (9) was obtained (85%) by ring expansion[7d] of the 2-(2-propenyl)thiolanium methylide from **38**. The sulfide material appears to consist of a single product (GLC and ^{13}C NMR) whose stability to heat suggests it has the *Z* configuration: bp 204 °C (754 mm); ^1H NMR δ 5.28 (td, J = 8.0 and 0.8 Hz, 1 H, olefinic proton), 2.6 and 2.2 (2 m, 8 H overall), 1.72 (d, $J \approx 0.8$ Hz, superimposed to a narrow m, 5 H overall, CH_3 plus two ring protons). The behavior of the single olefinic proton is consistent with the cis cyclic olefin, which is expected to undergo a rapid ring reversion resulting in averaging of the couplings with the adjacent methylene: ^{13}C NMR δ 136.7 (C_4), 124.3 (C_5), 35.6 (C_3), 32.8, 31.5, and 31.2 (C_2, C_7, and C_8, interchangeable), 24.6 and 24.5 (C_6 and CH_3, interchangeable). Anal. Calcd for $C_8H_{14}S$: C, 67.54; H, 9.92. Found: C, 67.52; H, 9.94.

(*Z*)-7,7-Dimethylthiacyclooct-4-ene (11) was obtained (80%) by ring expansion[7d] of the 4,4-dimethyl-2-vinylthiolanium methylide from **40**. The sulfide material appears to be made up of two products (GLC and ^{13}C NMR) in about an 85:15 ratio. GLC monitoring showed heating at 150 °C gradually and quantitatively converts the minor into the major component, indicating they are the *E* and *Z* olefins, respectively. No attempt was made to separate them. Purification was accomplished by distillation: bp 216 °C (760 mm); ^1H NMR δ 5.70 (m, 2 H, olefinic protons), 2.52 (m, 4 H), 2.42 (s, 2 H, C_8H_2), 2.14 (broad unresolved multiplet, 2 H), 0.97 (s, 6 H, CH_3); ^{13}C NMR δ 130.3 and 130.1 (C_4 and C_5, interchangeable), 44.2 (C_8), 39.4 (C_7), 37.1 (C_6), 34.6 (C_2), 30.6 (C_3), 27.3 (CH_3). Anal. Calcd for $C_9H_{16}S$: C, 69.17; H, 10.32. Found: C, 69.22; H, 10.27.

(*Z*)-1-(2-Phenylethyl)-Δ-4,5-thiocanium tetrafluoroborate (25) was obtained by the reaction (8 h, 25 °C) of **6** with 2-phenylethyl iodide (10% excess) in the presence of $AgBF_4$ (1 equiv) in CH_2Cl_2. The material (yield 99.3%) was a white waxy solid which could not be obtained in crystalline form. The ^1H NMR (60 MHz, acetone-d_6) was consistent with the title compound: δ 7.08 (m, 5 H, Ph ring), 5.58 (m, 2 H, olefinic protons), 3.5 (m, 6 H, α protons), 2.68 (m, 2 H, $PhCH_2$), other resonances at 3.13 and 2.13 (6 H overall). Anal. Calcd for $C_{15}H_{21}SBF_4$: C, 56.27; H, 6.61. Found: C, 56.33; H, 6.64.

1-(2-Phenylethyl)-*trans*-4,5-dihydroxythiocanium tetrafluoroborate (26) was synthesized from **25** by a one-pot oxidation–hydrolysis procedure. A solution of **25** (17 g, 0.053 mol) in AcOH (50 mL) and 30% H_2O_2 (27 mL, 0.238 mol) was refluxed for 13 h. The residue after evaporation under reduced pressure was dissolved in CH_2Cl_2 (50 mL) and extracted with water (4 × 50 mL). The combined extracts were back-extracted with CH_2Cl_2 and, after solvent evaporation under reduced pressure, gave a residue which was dried in vacuo (13 g, 69%). Its ^1H NMR (methanol-d_4) showed, besides the aromatic proton absorptions, two large bands centered at δ 3.5 and 2.1 whose overall intensities, however, are about 40% greater than expected on the basis of

Table III. Substituted *cis*-1-Thioniabicyclo[3.3.0]octane Salts. Analytical and Physical Data

cation	anion	mp, °C	C		H	
			calcd	found	calcd	found
13	PF_6^-	*a*	33.34	33.21	5.25	5.22
14	PF_6^-	*a*	33.34	33.38	5.25	5.22
15	PF_6^-	*a*	33.34	33.30	5.25	5.19
16	PF_6^-	158-160	33.34	33.27	5.25	5.13
17	picrate	164-165	46.75	46.82	4.97	5.01
18	picrate	270-272	45.16	45.22	4.87	4.91
19	Cl^-	*b*	46.53	46.61	7.25	7.31
20	$B(C_6H_5)_4^-$	210-211	80.16	80.15	7.16	7.31
21	picrate	163-164	35.79	35.68	3.23	3.15
22	picrate	167-168	35.79	35.87	3.23	3.38
23	picrate	185-187	39.85	39.99	3.60	3.70
24	picrate	180-182	39.85	39.70	3.60	3.59

[a] Since the precursor contained nonnegligible proportions of the diastereomeric homoallylic sulfide, the salt is contaminated (5-10%) by the corresponding diastereomer and melts over a wide range of temperatures. Due to the small amount of material available, purification by fractional crystallization was not feasible. [b] Uncrystallizable material.

the intensity of aromatic protons. As the purification of this material appeared to afford great difficulties, it was used as such in the subsequent base-catalyzed β-elimination (step iii of Scheme I). On the basis of the yield obtained in this latter step, it appeared to be at least 70% pure. Therefore, the yield of **26** is estimated to be ~50%.

***trans*-4,5-Dihydroxythiocane (27).** Crude **26** (13 g) in MeONa/MeOH (600 mL, 0.124 M) was refluxed for 2.5 h. The solution was neutralized with 20% aqueous NH_4Cl (60 mL) and evaporated to small volume. The aqueous residue was extracted with CH_2Cl_2 (5 × 50 mL) to give, after the solvent was removed and the residue dried in vacuo, a waxy solid (4.1 g, 70%). Crystallization from benzene–hexane (1:1) gave analytically pure product: mp 64–66 °C; ^1H NMR (benzene-d_6) δ 3.88 (narrow m, 2 H, CHOH), 3.56 (br s, 2 H, OH), 2.76 (m, 4 H, α protons), 1.96 (m, 6 H, β- and γ-protons); ^{13}C NMR δ 75.3 and 74.8 (C_4 and C_5, interchangeable), 34.1, 32.0, 30.6, 29.3 (C_2, C_3, C_6, and C_8, interchangeable), 25.1 (C_7). Anal. Calcd for $C_7H_{14}O_2S$: C, 51.82; H, 8.70. Found: C, 51.77; H, 8.65.

1-Methyl-*cis*-4,5-dihydroxythiocanium Trifluoromethanesulfonate (29). To an ice-cold aqueous solution of (*Z*)-1-methyl-Δ-4,5-thiocanium trifluoromethanesulfonate[14] (**28**; 2.92 g, 0.01 mol, in 8 mL of water) and 30% H_2O_2 (1.3 mL, 0.0115 mol) was added 40 μL of aqueous 0.078 M OsO_4 with stirring. After 4 h at 3–5 °C a second, equal portion of aqueous OsO_4 was added, and stirring was continued for 5 h more. The excess peroxide was destroyed with aqueous 2% $NaHSO_3$, and the mixture was evaporated under reduced pressure. The oily residue was taken up with acetone to dissolve the sulfonium salts, and the inorganic material was filtered off. Removal of the solvent in vacuo gave 2.62 g (84%) of a viscous uncrystallizable material, whose ^1H and ^{13}C NMR spectra are consistent with an ~1:1 mixture of isomers of the title compound. This is evinced by the presence in the proton spectrum (acetone-d_6) of two SCH_3 singlets, at δ 3.11 and 3.01 (overall 3 H), of roughly equal intensities. Other resonances are as follows: δ 4.0 and 3.7 (large unresolved m's, 8 H overall; two H's exchangeable by shaking with D_2O), 2.3 and 2.0 (large unresolved bands, 6 H overall). The ^{13}C spectrum has the expected overall 16 resonances; their assignment is not feasible, however, the two isomers being comparably populated. Nevertheless, the spectrum is consistent with the title structure as it shows the expected four lines in the C–OH region (δ 72.6, 72.0, 71.5, and 70.4) as well as the four lines expected in the region of the α ring carbons (δ 43.8 and 42.3, C_8; 39.5 and 38.8, C_2). Reduction of **29** (as the tetraphenylborate) by $LiAlH_4$ in THF[14] failed to give the expected diol sulfide. The material obtained was a mixture whose main component (separated by column chromatography) featured a terminal vinyl group (δ 6.2–4.9), two exchangeable protons at δ 3.5, and a SCH_3 singlet at δ 2.11, indicative of a ring-opened methyl sulfide.

1-Methyl-*cis*-4,5-bis[(2-tetrahydropyranyl)oxy]thiocanium Trifluoromethanesulfonate (30). Crude **29** (1.8 g, 5.5 mmol), 2,3-dihydropyran (3.7 g, 44 mmol), and *p*-toluenesulfonic acid monohydrate (0.133 g, 0.7 mmol) in 14 mL of dry DMF were stirred for 120 h at ambient temperature. After neutralization with 0.25 g of anhydrous K_2CO_3, solvent and unreacted dihydropyran were removed under reduced pressure, and the residue was dissolved in acetone (15 mL) and filtered. The filtrate was evaporated to 5 mL and poured into ether (50 mL) with vigorous stirring. The oily precipitate was separated, redissolved in acetone, reprecipitated as above, and dried in vacuo to give 1.7 g (63%) of an uncrystallizable viscous material. Its ^1H NMR (acetone-d_6) showed no absorption in the δ 6.4 region, indicating the excess 2,3-dihydropyran had been completely removed. The material appears to be made up of two isomers, in approximately a 3:1 ratio, as evinced by the presence of two SCH_3 singlets (3 H overall) at δ 3.17 and 3.13 (major). The change from the 1:1 isomeric ratio of the starting diol sulfonium salt may indicate that an equilibration process (via pyramidal inversion at sulfur) has taken place during pyranylation. Alternatively, it may be explained in terms of selective pyranylation of one of the two isomeric diols. The ^1H NMR further shows large unresolved multiplets at δ 4.8 (2 H), 3.7 (10 H), and 2.3 and 1.6 (18 H overall) and the absence of D_2O-exchangeable protons.

***cis*-4,5-Bis[(2-tetrahydropyranyl)oxy]thiocane (31).** Crude **30** (1.6 g, 3.24 mmol) in 9 mL of THF was added dropwise over 30 min to a stirred suspension of $LiAlH_4$ in THF (0.25 g, 6.5 mmol, in 9 mL at 15 °C. The mixture was stirred for 2 h, quenched with aqueous NH_4Cl, and filtered from inorganic salts. The filtrate was extracted with CH_2Cl_2 to give, after drying and solvent evaporation, 0.69 g (65%) of the title compound as an oily material. The ^1H NMR has the same general features as the starting material except for the disappearance of the S^+CH_3 resonances. However, the presence of a weak singlet at δ 2.10 indicates the $LiAlH_4$ reduction occurred in part (~20%) at one of the α ring carbons, leading to a ring-opened methyl sulfide.[10] No attempt was made to separate the acyclic from the cyclic sulfide, and the material was used as such in the subsequent dipyranylation–transannular cyclization to the *endo*-4-hydroxyl-1-thioniabicyclo[3.3.0]octane salt (**19**).

Picrate of *cis*-1-Thioniabicyclo[3.3.0]octane (12). A solution of (*Z*)-thiacyclooct-4-ene in CH_2Cl_2 (1 mmol in 2 mL) was treated with 1.03 mmol of trifluoromethanesulfonic acid and stirred for 2 h at room temperature. Removal of the solvent under vacuum quantitatively gave the title compound (triflate salt) as a viscous colorless oil. The ^{13}C NMR spectrum of this material is reported in Table I. The same product was obtained from (*E*)-thiacyclooct-4-ene (**1**). Metathesis to the picrate was performed by dissolving the triflate in the minimum amount of water and adding aqueous sodium picrate: yellow crystals; mp 256–58 °C after crystallization from ethanol (lit.[28] mp 257–58 °C). The procedure used for **12** was also employed for obtaining the bicyclic salts **13–18**, although in several cases the amount of starting material was much less than 1 mmol. The analytical data and melting points are reported in Table III.

***endo*- and *exo*-4-halogeno-*cis*-1-thioniabicyclo[3.3.0]octane salts 21, 23 and 22, 24** were obtained from (*Z*)-thiacyclooct-4-ene and (*E*)-thiacyclooct-4-ene (**1**), respectively, by treatment with halogen. To the homoallylic sulfide dissolved in CCl_4 (1 mmol

(28) Eastman, R. H.; Kritchevsky, G. *J. Org. Chem.* **1959**, *24*, 1428.

in 2 mL) was added a solution of Br_2 or Cl_2 in CCl_4 (1.05 mmol in 1 mL), causing the immediate formation of a solid. After 1 h at room temperature the solid was recovered as a highly hygroscopic, uncrystallizable material. The ^{13}C spectra were taken in D_2O solution. The respective picrates were obtained by metathesis with aqueous sodium picrate (see Table III).

***endo*-4-Hydroxy-*cis*-1-thioniabicyclo[3.3.0]octane (19)** was obtained as the chloride salt as follows. To an ethanol solution of the bis(pyranyl) derivatives **31** (0.69 g in 10 mL) was added aqueous 1 N HCl (11 mL) and the solution heated at reflux for 30 min. After neutralization with 1 N NaOH, the solution was concentrated under reduced pressure, and the aqueous residue was extracted with CH_2Cl_2 to remove any unreacted starting material. The aqueous phase was evaporated under reduced pressure and the residue extracted with MeOH to remove the inorganics. Evaporation of the solvent left 0.25 g (80%) of a viscous oil, whose ^{13}C spectrum (reported in Table I) showed it to be free of organic impurities.

***exo*-4-Hydroxy-*cis*-1-thioniabicyclo[3.3.0]octane (20)** was obtained as the triflate salt by treating *trans*-4,5-dihydroxythiocane (**27**) with trifluoromethanesulfonic acid in a procedure similar to that described for the parent cation **12**. The salt is a viscous uncrystallizable material; metathesis with hot aqueous sodium tetraphenylborate gave, after crystallization from H_2O/acetone, a crystalline solid (see Table III).

Attempted Transannular Cyclization of (*Z*)-4-Methylthiacyclooct-4-ene (9). Trifluoromethanesulfonic acid treatment of the title olefin for various lengths of time failed to produce the expected bicyclic 4-methyl derivatives. The material isolated after 2 h of reaction time was a sulfonium salt whose ^{13}C NMR spectrum (acetone-d_6) shows in the olefinic carbon region a singlet at δ 136.5 and a doublet at δ 126.7, indicative of the presence of the same $CCH{=}C(CH_3)C$ fragment present in the starting material. This structural feature finds support in the ^1H NMR spectrum which shows a low-field triplet of doublets (δ 5.62, 1 H, J = 8.0 and 1.0 Hz) which can be attributed to a single olefinic proton coupled to an allylic CH_3 group. The latter shows up as a narrow doublet (δ 1.81, 3 H, $J \simeq 1.0$ Hz). Further multiplet resonances are present at δ 3.8 (2 H), 3.4 (4 H), 2.9–2.5 (4 H), 2.2 (6 H), and 1.72 (6 H). Finally, and most revealing a CH_3 singlet is present at δ 1.26. The spectra are consistent with the dimeric product **32** (see Results and Discussion section). With progressively longer contact times, materials are produced whose NMR spectra become more and more complex and indicative of the presence of higher oligomers.

Registry No. 1, 64945-41-1; (±)-2, 66840-93-5; (±)-3, 66840-94-6; (±)-4, 73505-88-1; (±)-5, 73543-32-5; 6, 64945-38-6; (±)-7, 73543-33-6; (±)-8, 73543-34-7; 9, 73505-89-2; 10, 71411-34-2; 11, 73505-90-5; 12 triflate, 73505-92-7; 12 picrate, 73505-93-8; (±)-13 triflate, 73505-95-0; (±)-13 hexafluorophosphate, 73543-35-8; (±)-14 triflate, 73543-37-0; (±)-14 hexafluorophosphate, 73573-16-7; (±)-15 triflate, 73505-97-2; (±)-15 hexafluorophosphate, 73543-38-1; (±)-16 triflate, 73543-40-5; (±)-16 hexafluorophosphate, 73609-89-9; 17 triflate, 73505-99-4; 17 picrate, 73512-98-8; 18 triflate, 73506-01-1; 18 picrate, 73506-02-2; (±)-19 chloride, 73505-77-8; (±)-20 triflate, 73543-19-8; (±)-20 tetraphenylborate, 73609-88-8; (±)-21 bromide, 73505-78-9; (±)-21 picrate, 73543-21-2; (±)-22 bromide, 73543-22-3; (±)-22 picrate, 73573-13-4; (±)-23 chloride, 73505-79-0; (±)-23 picrate, 73543-24-5; (±)-24 chloride, 73543-25-6; (±)-24 picrate, 73573-15-6; 25, 73505-81-4; (±)-26, 73505-83-6; (±)-27, 73505-84-7; 28, 72050-57-8; (±)-*cis*-29, 73543-27-8; (±)-*trans*-29, 73543-29-0; (±)-*cis*-30, 73505-86-9; (±)-*trans*-30, 73543-31-4; (±)-31, 73505-87-0; 32, 73505-59-6; (*E*)-33, 73505-60-9; (*Z*)-33, 73505-61-0; 34, 73505-62-1; 35, 26551-55-3; (±)-(*E*)-36, 73543-16-5; (±)-(*Z*)-36, 73543-17-6; (±)-37, 73505-63-2; (±)-38, 73505-64-3; (±)-39, isomer 1, 73512-97-7; (±)-39, isomer 2, 73505-66-5; (±)-39, isomer 3, 73523-05-4; (±)-39, isomer 4, 73505-68-7; (±)-*cis*-40, 73505-70-1; (±)-trans-40, 73505-72-3; (±)-*cis*-41, 73505-74-5; (±)-*trans*-41, 73505-76-7; thietane, 287-27-4; crotyl bromide, 4784-77-4; 3,3-dimethylthietane, 13188-85-7; allyl bromide, 106-95-6; 2-methylallyl chloride, 1458-98-6; lithium diisopropylamide, 4111-54-0; 2-phenylethyl iodide, 17376-04-4.

Supplementary Material Available: Computed (force field) geometries, energies, and energy components for **1-t**, **1-c**, and **2–5**. (Table IV, bond distances; Table V, bond angles; Table VI, dihedral angles; Table VII, energies and energy components) (6 pages). Ordering information is given on any current masthead page.

Stereochemical Study on Nitro Tautomerization of Nitronate Adducts from Conjugate Addition of RMgX to a 4-Methoxy-1-nitronaphthalene System

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Addition of RMgX to 4-methoxy-1-nitronaphthalene (**1**) leads to formation of nitronate 1,4 adduct (**2**) together with lesser amounts of 1,6 addition product (**3**). On treatment with aqueous acetate–acetic acid buffer, **2** is converted into a nitronate anion which undergoes quick protonation at C-1 to give a mixture of *trans*- and *cis*-2-methyl-4-methoxy-1-nitro-1,2-dihydronaphthalene, with neat prevalence of the latter isomer. Conversion of kinetically favored cis compound into the more stable trans isomer occurs up to equilibrium, on prolonging times of the reaction. Prevailing formation of the less stable isomer is interpreted in terms of a sterically controlled approach of the proton to the carbon of the nitronate function of a nonplanar cyclohexadienic system in which prototropic attack must occur from the less hindered side. Conformational and configurational analyses based on interpretation of NMR spectra of reaction products showed the nitro group to exist preferentially "quasi-axial" in both cis and trans compounds. The large difference in stability between the two isomers can therefore be explained by the fact that the nitro and methyl groups are in an almost eclipsed reciprocal orientation in the cis isomer, whereas they are mutually "anti" oriented in the trans one. The influence of the size of the alkyl group on *aci*-nitro tautomerization and on cis–trans isomerization has been investigated: the conformational equilibrium of the nitronate anion is submitted to the steric effects of the alkyl substituent, which, moreover, strongly affect the isomerization process rate.

Nitronate adducts from conjugate addition of RMgX to nitroarenic systems and their reactivity toward reducing[1] and oxidizing agents[2] and toward Lewis acids[3] have been reported in previous papers.

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