Highly Stereoselective Reactions of Carbanions of Dithiabicyclo[3.1.0]hexane Derivatives

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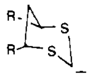
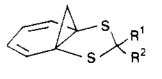
Abstract: Reactions of lithium derivaties of 7,9-dithiatricyclo[4.3.1.$0^{1,6}$]deca-2,4-diene (**3**) and 1,5-dimethyl-2,4-dithiabicyclo[3.1.0]hexane (**4**) with electrophiles (E) such as DCl, carbon dioxide, benzaldehyde, and alkyl halides resulted in the exclusive formation of products having E at the trans position (i.e., anti side to the cyclopropane ring) as judged by ^{1}H NMR, suggesting the selectivity of ca. 50:1. Lithiation followed by methylation of the two diastereomeric 8-deuterio derivatives of **3** has revealed that the kinetic stereoselectivity of the lithiation is by a factor of 9 with an isotope effect 2.8, thus showing that the trans stereoselectivity is mainly thermodynamically controlled. An ab initio molecular orbital study was performed for parent 2,4-dithiabicyclo[3.1.0]hexane (**12**) and its carbanion (**13**) with various conformations and the above stereoselectivity was explained in terms of the stereoelectronic effect in the carbanions. Comparison of the stereoelectronic effect between the carbanion of the dithiabicyclohexane and that of 1,3-dithiane was also discussed.

The reactivity of α-thiocarbanions is interesting both from synthetic and theoretical points of view.[2] One of the most important among them is 2-lithio-1,3-dithiane (**1**) (Corey–Seebach reagent) which is a carbonyl synthon of umpolung reactivity.[3–5] The conformationally fixed 1,3-dimethyl derivative of **1** (**2**) has been demonstrated by Eliel and his co-workers to have an intriguing stereoselectivity in the reactions with electrophiles.[6] The equatorial anion of **2** is thermodynamically much more stable than the corresponding axial anion, and only the products having electrophiles at the equatorial position were observed.[7] Theoretical interpretation for this equatorial selectivity has been given by Lehn and Wipff.[8]

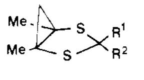
As part of our study on bridged heterocyclic compounds[9] we became interested in the reactivity of carbanions of dithiabicyclo[3.1.0]hexane derivatives **3** and **4** because we thought that these compounds would have the advantage of a rigid structure enabling us to study the stereoselectivity in the reaction of a carbanion of a five-membered dithiolane system.



1: R = H
2: R = Me



3: $R^1 = R^2 = H$
4: $R^1 = R^2 = D$



4: $R^1 = R^2 = H$
4-*d_2*: $R^1 = R^2 = D$

The purpose of this article is to report on the high stereoselectivity of the carbanions derived from **3** and **4** in the reactions with electrophiles and to give a theoretical interpretation for the selectivity.[10]

Scheme I

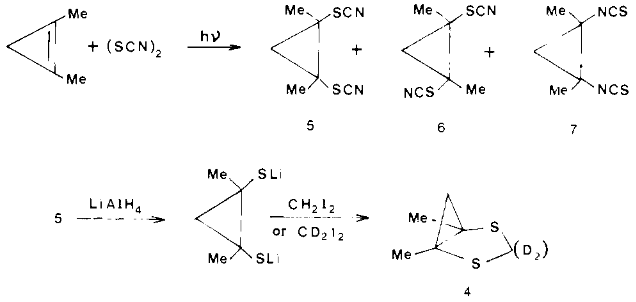


Table I. Reaction Products and Their Yields from Equation 1

product	E^+	E	yield, %
10a	DCl	D	50
11a			55
10b	CH_3I	CH_3	65
11b			98
10c	$PhCH_2Cl$	$PhCH_2$	27
11c			43
10d	Me_3SiCl	Me_3Si	57
11d			39
10e	$CH_2{=}CHCH_2Cl$	$CH_2{=}CHCH_2$	64
10f	$MeOCH_2Cl$	$MeOCH_2$	42
10g	PhCHO	PhCH(OH)	53
11g			54
10h	CO_2[a]	CO_2CH_3	54[b]
11h			80

[a] Carboxylic acids initially formed were esterified by diazomethane. [b] When introduction of carbon dioxide was carried out slowly, both trans (26%) and cis (14%) products were formed.

Results and Discussion

Syntheses of 3 and 4 and Their Deuteriated Derivatives. 7,9-Dithiatricyclo[4.3.1.$0^{1,6}$]deca-2,4-diene (**3**) was synthesized by a method previously reported by us.[9e] The synthesis of 1,5-dimethyl-2,4-dithiabicyclo[3.1.0]hexane (**4**) was performed by a route described in Scheme I. The photoreaction of 1,2-dimethylcyclopropene with thiocyanogen in carbon tetrachloride at −20 °C gave a 1:1 mixture (32%) of **5** and **6** and isothiocyanate **7** (7%). Since chromatographic separation of **5** and **6** was difficult, their mixture was directly subjected to reduction by lithium

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(2) Block, E. *Reactions of Organosulfur Compounds*; Academic Press: New York, 1978. Streitwieser, A., Jr.; Juaristi, E.; Nebenzahl, L. L. *Comprehensive Carbanion Chemistry. Part A*; Buncel, E., Durst, T., Eds.; Elsevier: Amsterdam, 1980; Chapter 7.

(3) Corey, E. J.; Seebach, D. *Angew. Chem., Int. Ed. Engl.* **1965**, *4*, 1075, 1077.

(4) Seebach, D. *Angew. Chem., Int. Ed. Engl.* **1969**, *8*, 639. Grobel, B.-T.; Seebach, D. *Synthesis* **1977**, 357.

(5) Seebach, D. *Angew. Chem., Int. Ed. Engl.* **1979**, *18*, 239.

(6) Eliel, E. L.; Hartmann, A. A.; Abatjoglou, A. G. *J. Am. Chem. Soc.* **1974**, *96*, 1807.

(7) A similar equatorial preference has been reported also for the 1,3,5-trithiane system. Fukunaga, M.; Arai, K.; Iwamura, H.; Oki, M. *Bull. Chem. Soc. Jpn.* **1972**, *45*, 302. Fukunaga, M.; Sugawara, T.; Oki, M. *Chem. Lett.* **1972**, 55. Fukunaga, M.; Oki, M. *Ibid.* **1972**, 1081.

(8) Lehn, J.-M.; Wipff, G. *J. Am. Chem. Soc.* **1976**, *98*, 7498.

(9) (a) Okazaki, R.; O-oka, M.; Tokitoh, N.; Shishido, Y.; Inamoto, N. *Angew. Chem., Int. Ed. Engl.* **1981**, *20*, 799. (b) Okazaki, R.; Takai, H.; O-oka, M.; Inamoto, N. *Tetrahedron Lett.* **1982**, *23*, 4973. (c) Okazaki, R.; O-oka, M.; Tokitoh, N.; Shishido, Y.; Hasegawa, T.; Inamoto, N. *Phosphorus Sulfur* **1983**, *16*, 161. (d) Okazaki, R.; Hasegawa, T.; Shishido, Y. *J. Am. Chem. Soc.* **1984**, *106*, 5271. (e) Okazaki, R.; O-oka, M.; Tokitoh, N.; Inamoto, N. *J. Org. Chem.* **1985**, *50*, 180.

(10) Part of this work was reported in a preliminary form: Okazaki, R.; O-oka, M.; Akiyama, T.; Inamoto, N. *Heterocycles* **1982**, *18*, 241.

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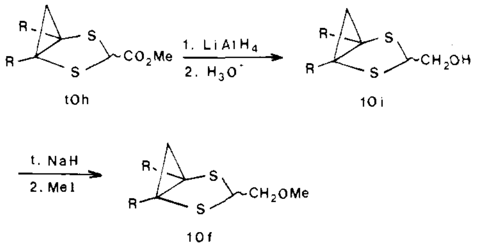
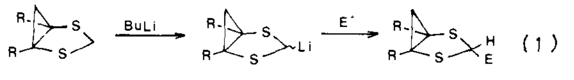
Scheme II



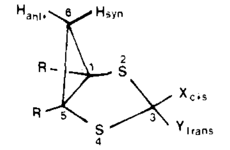
aluminum hydride followed by the reaction with diiodomethane to afford **4** in 94% yield from **5**. Deuteriated compounds **3**-d_2 and **4**-d_2 were prepared similarly with CD_2I_2 instead of CH_2I_2.

Reactions of Carbanions of 3 and 4 with Electrophiles. Trans Selectivity.[11] Lithiation of **3** and **4** with butyllithium in tetrahydrofuran (THF) at −78 °C followed by quenching with electrophiles (E^+) afforded products **10t** and **11t**, respectively (eq 1).[12]



3, 4 **8, 9** **10t, 11t**

The results are listed in Table I. In all cases except for the reaction with carbon dioxide, the products were a single isomer as judged by ^{1}H NMR, suggesting the selectivity of ca. 50:1.[13] The products in the reaction with carbon dioxide were dependent on the reaction conditions. Thus, while slow introduction of carbon dioxide gas into a solution of the carbanion **8** or **9** followed by acidification and treatment with diazomethane gave **10ht** and **10hc** of **11ht** and **11hc**, respectively, rapid introduction of the gas into a more dilute solution of **8** or **9** afforded only **10ht** or **11ht**, respectively, within the limit of detection by ^{1}H NMR.[11,13]



10ht: R = $(CH{=}CH)_2$, X = H, Y = CO_2Me
10hc: R = $(CH{=}CH)_2$, X = CO_2Me, Y = H
11ht: R = Me, X = H, Y = CO_2Me
11hc: R = Me, X = CO_2Me, Y = H

The stereochemical assignment of the esters **10h** and **11h** was made by ^{1}H NMR with use of a lanthanide shift reagent, Eu(fod)$_3$-d_{27}; the chemical shifts of one of the methylene protons on C_6 (i.e., H_{syn}) in **10hc** and **11hc** were highly affected by concentration of the shift reagent, whereas those in **10ht** and **11ht** were affected to a minor extent. It is concluded, therefore, that carbon dioxide reacts with **8** on the anti side to the cyclopropane leading to the stereoselective formation of the trans ester **10ht** under "rapid introduction" conditions. The concurrent formation of **10hc** under "slow introduction" conditions is most likely explained in terms of abstraction by **8** of the hydrogen on C_3 of **10ht** whose acidity is enhanced by introduction of the carboxylate function. This sort of partial equilibration during quenching is not an uncommon occurrence in carbanion chemistry.[14]

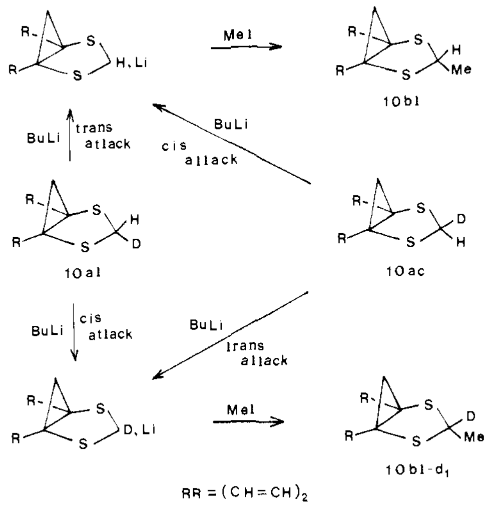
The esters **10ht** and **10hc** were converted, via alcohols **10it** and **10ic**, into methyl ethers **10ft** (72% from **10ht**) and **10fc** (55% from **10hc**), respectively, by routes depicted in Scheme II. The ether **10f** obtained in the reaction of the carbanion **8** with chloromethoxymethane was identical with the product formed from the ester **10ht** but not with that from **10hc**, demonstrating that the reaction with the alkyl chloride also proceeded in a trans fashion as in the case of carbon dioxide.

Table II. Chemical Shifts of Protons on C_3 of **10** and **11**

compd	H_{trans}	H_{cis}	$\Delta\delta^a$
3	4.20	3.68	0.52
10ft		4.42	1.18
10fc	5.60		
10ht		4.74	0.59
10hc	5.33		
10it		4.39	0.89
10ic	5.28		
4	3.69	3.57	0.12
11ht		4.44	0.26
11hc	4.70		
11it		4.24	0.32
11ic	4.56		

^{a} $\Delta\delta = \delta_{H(trans)} - \delta_{H(cis)}$.

Scheme III



In Table II are listed the chemical shifts of protons on C_3 for compounds whose structure has been chemically unequivocally established along with those for **3** and **4**. Since H_{trans}'s resonate at lower field than H_{cis}'s in all cases for **10** and **11**, the lower resonating protons in **3** and **4** are also reasonably assigned H_{trans} as shown in Table II. When **3**-d_2 and **4**-d_2 were allowed to react with butyllithium and then with hydrochloric acid, **3**-d_1-**c** (i.e., **10ac**) and **4**-d_1-**c** (i.e., **11ac**) were obtained. In these monodeuteriated products only H_{trans}'s were observed in ^{1}H NMR, whereas in **10at** and **11at** formed in the reactions of **8** and **9** with DCl as a quenching reagent (Table I) only H_{cis}'s were observed. These findings clearly demonstrate that the carbanions **8** and **9** react in a trans fashion again in the reactions with HCl and DCl. On the basis of these observations that carbon dioxide, chloromethoxymethane, and proton (and deuteron) attack the carbanions from the anti side to the cyclopropane ring, we consider that the other electrophiles would also react in a similar way (i.e., trans attack).

The above stereoselectivity was not affected by the amount of hexamethylphosphoric triamide (HMPA) added to the solvent. Thus, either in the complete absence or in the presence of 20 equiv of HMPA, **3** and **4** gave only **10bt** and **11bt**, respectively, in the reaction with methyl iodide. This strongly suggests that the intermediate giving stereoselectively the trans products is a carbanion or carbanion pair rather than a covalent lithium compound of oligomer thereof.

Thermodynamic vs. Kinetic Control. In order to determine whether the high stereoselectivity of the above reactions is due to kinetic control (i.e., the trans hydrogen is replaced by lithium more rapidly than the cis) or to thermodynamic control (i.e., a more stable trans lithium compound is eventually formed regardless of which proton is abstracted in the first step), we carried out a series of reactions depicted in Scheme III using mono-

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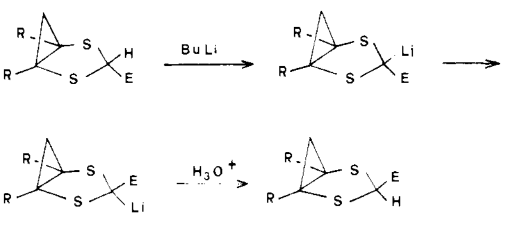
(11) Throughout this article, the positions R^1 and R^2 in **3** and **4** are defined as cis and trans and abbreviated as c and t in compound numbers, respectively.

(12) Lithiation of **3**, but not **4**, was effected also by lithium diisopropylamide (LDA). For example, the reaction of **3** with LDA under otherwise the same conditions as those with butyllithium followed by treatment with methyl iodide afforded **10bt** in 62% yield.

(13) Examination of NMR spectra of mixtures of **10ht** and **10hc** indicated that cross-contamination of the two isomers could have been detected at about the 2% level.

(14) For example, see: Abatjoglou, A. G.; Eliel, E. L.; Kuyper, L. F. *J. Am. Chem. Soc.* **1977**, *99*, 8262.

Scheme IV



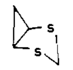
deuteriated compounds **10at** and **10ac**.

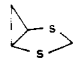
This technique is essentially the same as that used by Eliel to solve a similar problem for the lithiated dithiane **2**.[6] From deuterium contents determined by mass spectrometry for the methylated products **10bt** and **10bt-*d***$_1$ the isotope effect k_H/k_D and the rate ratio k_{trans}/k_{cis} in the hydrogen abstraction process were determined as 2.8 and 9.0, respectively. The latter value suggests that not only H_{trans} but also H_{cis} is abstracted though to a minor extent. The trans selectivity of ca. 50:1 observed (vide infra), however, clearly indicates that the cis anion formed from abstraction of H_{cis} must be converted rapidly into the trans anion before quenching with electrophiles. Thus the high selectivity of the reactions rests on a thermodynamic control rather than a kinetic control.

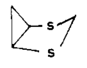
The values k_H/k_D and k_{trans}/k_{cis} obtained for our compounds are similar to those reported for 4,6-dimethyl-1,3-dithiane (i.e., 2.5 and 8.6, respectively).[6] However, in our compound, H_{trans} anti to C_6 with regard to a ring $C_1S_2C_3S_4C_5$ is more reactive, while in the dithiane $H_{equatorial}$ syn to C_5 with regard to a hypothetical ring $S_1C_2S_3C_4C_6$ is more reactive. The reason for this interesting difference will be discussed later.

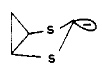
If the trans anion is thermodynamically more stable than the cis anion, epimerization from the trans product to the cis involving conversion from a cis anion to a more stable trans one as described in Scheme IV should occur. This indeed was found to be the case for the esters **10h** and **11h**. Thus, **10ht** was converted into **10hc** in 74%; the ester obtained after such treatment did not contain any **10ht** as judged by ^{1}H NMR. In the reactions of **11ht** the cis/trans ratio was determined by GLC analysis to be 99.1:0.9, showing a very high selective conversion.[15]

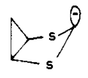
Reaction Pathways Expected by Calculation and Rationale for the Trans Selectivity. Ab intio Hartree–Fock calculations have been done for various conformers of the parent 2,4-dithiabicyclo[3.1.0]hexane (**12**) and its carbanion **13** in order to elucidate the reasons for the high trans selectivity.[16] For comparison calculations were also performed for 1,3-dithiane (**14**) and its anion **1**.

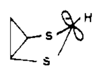

12C

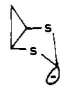

12P

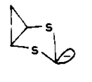

12B

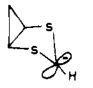

13Bt

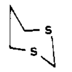

13Bc

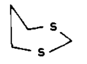

13Bs

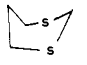

13Ct


13Cc


13Cs


14C


14P


14B

The geometries of these conformers were determined by the energy gradient method. The basis set we have employed in the geometry optimizations is 3-21G$^{(*)}$ or 3-21+G$^{(*)}$.[17] In order to obtain more reliable energy estimates, we have repeated the calculations with the 6-31G* or 6-31+G$^{(*)}$ basis set at the 3-21G$^{(*)}$ or 3-21+G$^{(*)}$ optimized geometries. The exponent of a diffuse sp shell function for the anionic carbon atoms was chosen to be 0.04.[18] The calculated relative energies and geometries are summarized in Tables III and IV.[19]

Table III. Total Energies of **12**, **13**, **14**, and **1** Calculated by the ab Initio MO Method[a]

compd	3-21G$^{(*)\,b,c}$	6-31+G$^{(*)\,d,e}$
12B	0.0[f]	0.0[g]
12C	0.5	0.0
12P	1.8	1.5
13Bt	0.0[h] (0.0)[i]	0.0[j] (0.0)[k]
13Bc	12.4	12.8
13Bs	14.3	16.7
13Ct	16.9	14.3
13Cc	2.4 (1.4)	0.9 (1.0)
13Cs	17.6	19.6
14B	5.5	5.5
14C	0.0[l]	0.0[m]
1Ce	0.0[n] (0.0)[o]	0.0[p] (0.0)[q]
1Ca	10.2	7.6 (7.4)

[a] Relative energies (kcal mol^{-1}) to the most stable conformer in each case of **12**, **13**, **14**, and **1**. [b] d orbitals are taken into account on sulfur (exponent: 0.65). [c] Values in parentheses were calculated with 3-21+G$^{(*)}$, where a diffuse sp shell on the anionic carbon (exponent: 0.04) is also taken into account. [d] For carbanions **13** and **1**, the calculations were carried out with geometries obtained by 3-21G$^{(*)}$ with d orbitals on sulfur (exponent: 0.65) and a diffuse sp shell (exponent: 0.04) being taken into account. For neutral molecules **12** and **14**, the calculations were carried out with 6-31G*. [e] Values in parentheses were calculated with 6-31+G*, where a diffuse sp function (exponent: 0.04) is taken into account. [f] −945.3898 hartrees. [g] −949.9442 hartrees. [h] −944.7472 hartrees. [i] −944.7612 hartrees. [j] −949.3097 hartrees. [k] −949.3098 hartrees. [l] −946.6008 hartrees. [m] −951.1499 hartrees. [n] −945.9571 hartrees. [o] −945.9726 hartrees. [p] −950.5138 hartrees. [q] −950.5138 hartrees.

In order to estimate the barrier height for the interconversion between **12B** and **12C**, we calculated the energies for a hypothetical geometry **12P**. The geometry optimizations were performed under the constraint that the five atoms (i.e., $C_1S_2C_3S_4C_5$) in **12P** are in a plane. Although this planar form is not the true saddle point for the boat–chair conversion, the energies at this geometry would provide reasonable estimates for the barrier height. For the cis–trans inversions of carbanions, we have taken the sp^2 forms (**13Bs** and **13Cs**) where the $S_2C_3HS_4$ part is planar. The results for these hypothetical forms are also included in Table III.

Inspection of Table III suggests the following interesting features for the relative stability of these compounds. (1) The boat and chair forms of **12** (i.e., **12B** and **12C**) are more stable than the planar form (**12P**) and there is no essential difference in stability between **12B** and **12C**.[20] Since **12P** is considered to be

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(15) Conversions involving a substituent (E in Scheme IV) other than the methoxycarbonyl group were also tried, but the carbanions were too unstable to decompose even at −78 °C in those cases.

(16) In **12**, **13**, **14**, and **1**, the following abbrevations are used. B, boat; C, chair; P, planar (for $C_1S_2C_3S_4C_5$ in **12** and for $C_6S_1C_2S_3C_4$ in **14**); t, trans; c, cis; s, sp^2 anion; e, equatorial; a, axial.

(17) Pietro, W. J.; Francl, M. M.; Hehre, W. J.; DeFrees, D. J.; Pople, J. A.; Binkley, J. S. *J. Am. Chem. Soc.* **1982**, *104*, 5039.

(18) Chandrasekhar, J.; Andradej, J. G.; Schleyer, P. v. R. *J. Am. Chem. Soc.* **1981**, *103*, 5609.

(19) For ready comparison, the same numbering is used for both dithiabicyclohexanes **12** and **13** and dithianes **14** and **1** in this and the following sections and in Table IV (for the numbering, see Schemes VIII and IX), although, for the dithianes, the numbering does not coincide with that required by IUPAC nomenclature.

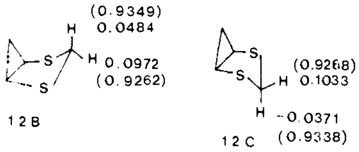
(20) It should be noted that the stability of **12B** is approximately equal to that of **12C** in spite of unfavorable steric repulsion between H_{cis} on C_3 and H_{syn} on C_6; the distance between these two hydrogens obtained from 3-21G$^{(*)}$ calculation is 2.66 Å, which is very close to the sum (2.4 Å) of van der Waals radii of two hydrogens. Bicyclo[3.1.0]hexane and its derivatives are known to have a boat form. Mastryukov, V. S.; Osina, E. L.; Hilderbrandt, R. L. *J. Am. Chem. Soc.* **1977**, *99*, 6855. Cook, R. L.; Malloy, T. B., Jr. *J. Am. Chem. Soc.* **1974**, *96*, 1703. Grostic, M. F.; Duchamp, D. J.; Chidester, C. G. *J. Org. Chem.* **1971**, *36*, 2929. Morris, D. G.; Murray-Rust, P.; Murry-Rust, J. *J. Chem. Soc., Perkin Trans. 2* **1977**, 1577. See also: Mjoberg, P. J.; Ralowski, W. M.; Ljunggren, S. O. *J. Mol. Spectrsoc.* **1976**, *60*, 179. Ab initio calculations on the stability of a boat form in bicyclo[3.1.0]hexane and its heteroanalogues including **12** will be reported elsewhere.

Table IV. Bond Lengths (Å) and Bond Angles (deg) in **12**, **13**, **14**, and **1** As Determined by Calculations (3-21G$^{(*)}$)[a] and Observed Values of Some Related Compounds, **17** and **18**

compd	S2–C3 (S4–C3)	S2–C1 (S4–C5)	C1–C6 (C5–C6)	C1–C5	∠S2C3S4	∠C3S2C1 (∠C3S4C5)	∠C5C6C1	∠S2C1C6 (∠S4C5C6)	∠α[b]	∠β[b]
12C	1.824	1.790	1.511	1.509	109.7	96.8	59.9	119.1	110.8	149.8
12B	1.824	1.784	1.513	1.511	110.6	96.0	59.9	121.2	113.1	149.8
13Cc	1.791	1.831	1.519	1.513	104.6	98.3	59.7	118.5	111.6	138.8
	(1.795)	(1.828)	(1.519)	(1.515)	(105.0)	(97.7)	(59.9)	(118.6)	(111.6)	(138.3)
13Bt	1.775	1.827	1.517	1.513	106.8	97.7	59.8	119.6	112.8	140.4
	(1.783)	(1.824)	(1.517)	(1.515)	(107.0)	(97.3)	(59.9)	(120.0)	(113.1)	(140.4)
17[c]	1.792	1.824	1.518		114.5	99.2	116.7	112.8		
14C	1.813	1.818	1.540		114.6	98.4	112.6	113.7	121.8	118.9
14B	1.813	1.835	1.540		115.3	101.1	113.4		129.5	125.1
18[d]	1.782	1.830	1.526		109.4	105.4	112.7	113.0		
1Ce	1.756	1.841	1.550		113.9	103.8	113.3	112.9	124.3	126.1
	(1.761)	(1.838)	(1.547)		(113.9)	(103.8)	(113.3)	(112.9)	(124.1)	(125.7)
1Ca	1.857	1.817	1.549		107.8	94.6	113.4	112.8	122.4	107.1
	(1.834)	(1.815)	(1.548)		(109.0)	(95.5)	(113.5)	(112.7)	(122.8)	(108.7)

[a] Values in parentheses for carbanions **13Cc**, **13Bt**, **1Ce**, and **1Ca** are those obtained with 3-21+G$^{(*)}$. [b] α and β are dihedral angles between two planes $C_1C_6C_5$ and $C_1S_2S_4C_5$ and between two planes $S_2C_3S_4$ and $C_1S_2S_4C_5$, respectively. [c] Observed values (ref 30). [d] Observed values (ref 27a). Compound **18** is dimeric and one of the two sulfur atoms is coordinated to lithium while the other is not. Bond lengths and angles cited here are those involving the non-lithiated sulfur.

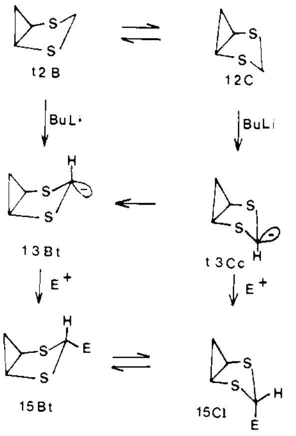
Scheme V



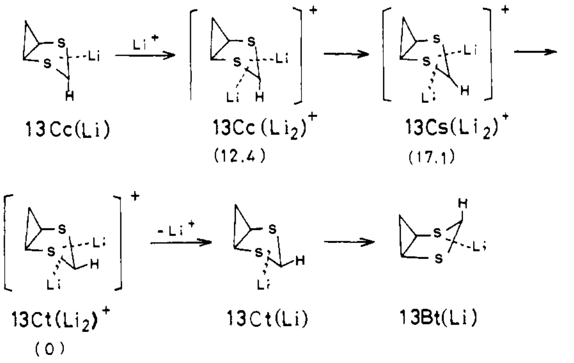
rather close to the transition state of inversion **12B** ⇌ **12C**, the relative low value (1.5 kcal mol^{-1}) of **12P** suggests that the inversion can occur very rapidly even at low temperatures like −78 °C where our experiments were carried out. This is not surprising considering that the sulfur-containing heterocycle is a five-membered ring, but it is in sharp contrast to a large energy difference (5.5 kcal mol^{-1}) between **14B** and **14C**. (2) For carbanion **13** note the following: (i) The most stable conformer is a trans anion of the boat form **13Bt** and the next stable one is a cis anion of the chair form **13Cc**. (ii) **13Bc** and **13Ct** are about 13 kcal mol^{-1} less stable than **13Bt** and **13Cc**, respectively. We have further calculated (6-31+G*) the energies of **13Bt** and **13Cc** using geometries optimized with the 3-21+G$^{(*)}$ basis set, but the results were almost identical with those obtained with the 6-31+G$^{(*)}$ basis set. (iii) Carbanions of sp^2 type (i.e., **13Bs** and **13Cs**) are very unstable compared with those of sp^3 type. Such inversions as **13Bt** ⇌ **13Bc** and **13Cc** ⇌ **13Ct**, therefore, are very unlikely, at least if it takes place unimolecularly, because **13Bs** and **13Cs** are rather close, though not equal, to the transition state of the above inversion.[21]

As is well-known the orientation of electrophilic reactions is controlled by the properties of lowest unoccupied molecular orbital (LUMO). The LUMO coefficients (obtained by STO-3G calculations with 3-21G$^{(*)}$ optimized geometry) of methylene hydrogens on C_3 of **12B** and **12C** given in Scheme V suggest that the trans hydrogen in **12B** and the cis hydrogen in **12C** are more reactive than the cis and trans hydrogen in **12B** and **12C**, respectively. The gross orbital charges of these hydrogens are also shown in parentheses in Scheme V. Here again, the former two hydrogens are more positive than the latter two hydrogens. These frontier-orbital- and charge-controlled reactions will result in the stable **13Bt** and **13Cc** carbanions.

Scheme VI



Scheme VII



These results of calculations indicate that the product **15** is formed via a route **12B** (⇌ **12C**) → **13Bt** → **15Bt** (⇌ **15Ct**), not via a route **12C** (⇌ **12B**) → **13Cc** → **13Bt** → **15Bt** (Scheme VI), since the unimolecular conversion **13Cc** ⇌ **13Bt** seems difficult at least from a theoretical point of view. Our experimental results show, however, that k_{trans}/k_{cis} is 9 for **3** while trans selectivity in the product formation is ca. 50:1. This indicates that the conversion from the cis anion to the trans anion must occur during the reaction. Thus the reaction pathways actually occurring in the present system are considered as follows. At the beginning of the reaction, **12B** is equilibrated with **12C** and the abstraction of H_{cis} from **12C** by butyllithium also takes place to give **12Cc** in parallel with the abstraction of H_{trans} from **12B** as the major process. **13Cc** formed from **12C** is rapidly converted into more stable **13Bt** under the reaction conditions. **13Bt** thus formed from both **12B** and **12C** is quenched with an electrophile to give **15Bt** which is then equilibrated with **15Ct**.

One of the possible explanations for the rapid conversion of the cis anion of a chair form into the trans anion of a boat form is considered to be a non-unimolecular process involving exchange

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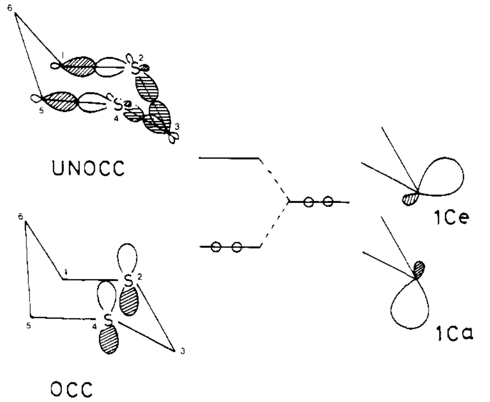
(21) Inversion barriers have been computed for $^{-}CH_2SH$, $^{-}CH_2SMe$, and CH_3^{-} to have 11.0,[22] 11.3,[8] and 13.8[23] kcal mol^{-1}, respectively.

(22) Bernardi, F.; Csizmadi, I. G.; Mangini, A.; Schlegel, H. B.; Whangbo, M. H.; Wolfe, S. *J. Am. Chem. Soc.* **1975**, *97*, 2209.

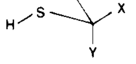
(23) (a) Wolfe, S.; Tel, L. M.; Liang, J. H.; Csizmadia, I. G. *J. Am. Chem. Soc.* **1972**, *94*, 1361. (b) Clark, T.; Schleyer, P. v. R.; Pople, J. A. *J. Chem. Soc., Chem. Commun.* **1978**, 137.

Scheme VIII



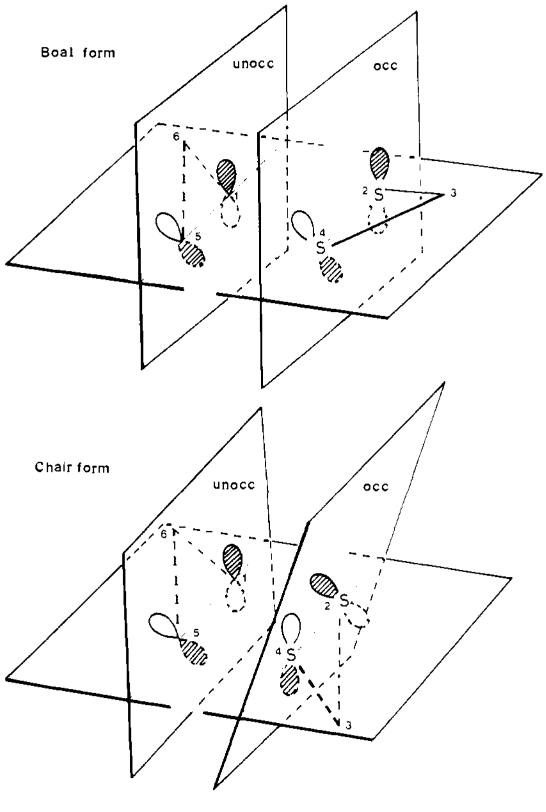
of lithium ions.[24] In order to check this possible involvement of lithium ions in lowering the energy barrier for the conversion, we have carried out calculations (6-31G*) for the process **13C(Li)** $\rightleftharpoons$ **13Bt(Li)** assuming the reaction paths shown in Scheme VII. Relative total energies for the three **13C(Li$_2$)$^+$** species with regards to the most stable one (**13Ct(Li$_2$)$^+$**) are shown in parentheses below the compound number (kcal mol^{-1} unit). The inversion barrier from the cis to th trans anion is dramatically decreased to 4.7 kcal mol^{-1}.[25] Although the actual process would be more complex and further detailed experiments must be awaited to establish a definitive mechanism, the present calculations suggest that lithium ions may play an important role in decreasing the inversion barrier.[26]

Factors Governing the Conformational Stability of Carbanions 8, 9, and 1. As described previously, Eliel and his co-workers have reported that in dithiane anion **2** the equatorial anion is thermodynamically much more stable than the axial anion.[6] Recently, X-ray crystal structural analyses of 2-lithio-2-methyl- and 2-lithio-2-phenyl-1,3-dithiane have been reported by Seebach, Dunitz, and their co-workers and the lithium has been shown to occupy the equatorial position.[27] Theoretical interpretation for the stability of the equatorial anion was given by Lehn and Wipff[8] with **16** as a model compound. According to their calculations, **16e** where the lone pair (lp) of the carbanion is antiperiplanar (app) to the S–H bond is 9 kcal mol^{-1} more stable than **16a**, and they ascribed this difference in stability both to stabilizing interaction between C$^-$lp and σ^*(app S–H) in **16e** and to repulsive interaction between C$^-$lp and Slp(app to C$^-$lp) in **16a**.



16e: X = –; Y = H
16a: X = H; Y = –

Scheme IX



In order to further shed light on the picture of the stabilization (or destabilization) of α-thiocarbanion, we have carried out calculations for 1,3-dithiane (**14**) and its anion **1** (Tables III and IV) and attempted to analyze orbital interactions in them. The pertinent points are as follows. (i) In a neutral molecule, the chair form is ca. 5 kcal mol^{-1} more stable than the boat form. This is in good agreement with the observed[28] difference in enthalpy between both forms ($\Delta H° = 3.4$ kcal mol^{-1}) for 2,5-di-*tert*-butyl-1,3-dithiane.[29] (ii) In the anion of the chair form, the equatorial anion is ca. 8 kcal mol^{-1} more stable than the axial anion. The value is comparable to the value (9 kcal mol^{-1}) reported for **16**. (iii) The relative stability between **1Ce** and **1Ca** can be interpreted by considering the orbital interaction of C$^-$lp with the a′ MOs of the dithiane part. As shown in Scheme VIII, the highest energy occupied MO in the a′ symmetry of dithiane is the Slp and the a′ lowest energy unoccupied MO is the CSC σ-type orbital, respectively. In **1Ce** the C$^-$lp orbital preferably interacts with the unoccupied MO to stabilize the system. The difference of geometries between **1Ce** and **14C** clearly demonstrates the importance of this delocalization interaction. The S_2–C_1 (S_4–C_5) distance is lengthened (1.837 Å in **1Ce** vs. 1.818 Å in **14C**) and the S_2–C_3 (S_4–C_3) distance is shortened (1.761 Å in **1Ce** vs. 1.813 Å in **14C**) in **1Ce** because the unoccupied MO is antibonding at the S_2–C_1 (S_4–C_5) bond and bonding at the S_2–C_3 (S_4–C_3) bond region. In **1Ca**, on the other hand, the predominant orbital interaction is the π-type repulsive interaction between the C$^-$lp and Slp. Thus the S_2–C_3 (S_4–C_3) distance increases (1.834 Å in **1Ca** vs. 1.813 Å in **14C**) while the S_2–C_1 (S_4–C_5) bond is not affected in **1Ca** (1.815 Å in **1Ca** vs. 1.818 Å in **14C**).

For the dithiabicyclo[3.1.0]hexane carbanion, the present calculations showed that **13Bt** and **13Cc** are more stable than **13Bc** and **13Ct**. This result is consistent with the postulate of Eliel et al. and Lehn and Wipff because C$^-$lp is app to the S_2–C_1 (S_4–C_5) bond in **13Bt** and **13Cc**, while C$^-$lp is app to Slp in **13Bc** and **13Ct**,

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[24] A mechanism of the inversion of methyllithium involving two lithium ions has been proposed by ab initio calculation.[23b]

[25] When optimization was carried out by removing the upper lithium ion from both **13Cc(Li$_2$)$^+$** and **13Cs(Li$_2$)$^+$**, each system was found to approach **13Bt(Li)** via **13Ct(Li)**.

[26] In our experiments, HMPA was not present during the lithiation procedure since it was added just before the addition of electrophiles. Therefore, lithium ions have the possibility of taking part in the inversion process even in the reaction in the presence of HMPA. Eliel et al. have reported,[14] however, that the lithiation–methylation of 2-phenyl-1,3-dithiane in the presence of HMPA (in this case HMPA was present on the lithiation) results in the formation of equatorial methyl products with an extremely high selectivity, suggesting that, even in a solvent (HMPA) separated ion pair, the inversion from the thermodymamically less stable axial carbanion to the more stable equatorial carbanion takes place very fast. Although these authors have not mentioned the mechanism of this particular inversion process, we believe that one possible explanation for the facile inversion is participation of a lithium ion of another molecule of butyllithium in lithiation.

[27] (a) Amstutz, R.; Seebach, D.; Seiler, P.; Schweizer, B.; Dunitz, J. D. *Angew. Chem., Int. Ed. Engl.* **1980**, *19*, 53. (b) Amstutz, R.; Dunitz, J. D.; Seebach, D. *Ibid.* **1981**, *20*, 465. See also: (c) Amstutz, R.; Laube, T.; Schweizer, W. B.; Seebach, D.; Dunitz, J. D. *Helv. Chim. Acta* **1984**, *67*, 224.

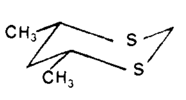
[28] Eliel, E. L.; Hutchins, R. O. *J. Am. Chem. Soc.* **1969**, *91*, 2703.

[29] Since 2,5-di-*tert*-butyl-1,3-dithiane has a twist-boat form,[28] the comparison is necessarily approximate.

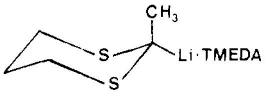
[30] McPhail, A. T.; Onan, K. D.; Koskimies, J. *J. Chem. Soc., Perkin Trans. 2* **1976**, 1004.

respectively. In contrast to the case of dithiane, the boat form, **13Bt**, was calculated to be more stable than the chair form, **13Cc**, by 1.0 kcal mol^{-1}. For the neutral species there is no difference in stability between the boat form **12B** and the chair form **12C** although a substantial steric repulsion is expected between H_{cis} on C_3 and H_{syn} on C_6.[20] The relative stabilization of the boat form is mainly attributed to the orbital interaction between the Slp and C_1–C_5 pseudo-π^* orbital. As is seen in Scheme IX, such orbital interaction is more favorable in the boat form than in the chair form. In general the S_2–C_1 (S_4–C_5) bond distances in **12** and **13** are shorter than those of the corresponding dithiane counterparts (i.e., **12C** vs. **14C**, **12B** vs. **14B**, **13Cc** vs. **1Ce**) by 0.01–0.05 Å which implies the existence of S–C π-type conjugation in the dithiabicyclo species. The angles α and β given in Table IV also indicate the importance of the π-conjugation in determining the relative stability betwee the boat and chair conformers in the bicyclo compound. In the dithiane, the angles α and β in the boat form are larger than those in the chair form by 8° and 6°, respectively, implying the relative stabiltity is controlled by the repulsion between the terminal H atoms on C_3 and C_6. On the other hand, these two angles are nearly the same in both conformers of the dithiabicyclo species. This result indicates that the geometry is also kept to have an efficient π-conjugation in the boat form.

In Table IV there are also listed the geometrical data on related compounds, *r*-4,*c*-6-dimethyl-1,3-dithiane (**17**) and 2-lithio-2-methyl-1,3-dithiane (tetramethylenediamine complex) (**18**), as determined by X-ray crystallographic analysis. Geometries obtained by the present calculations for **14C** and **1Ce** are in good agreement with these observed values.



17



18

As discussed above, the theoretical characterization of geometries is important for having a deeper insight to the reactivities of thiocarbanions and the electronic origin in determining the relative stability of various conformations of thiocarbanions.

Experimental Section

1,5-Dimethyl-2,4-dithiabicyclo[3.1.0]hexane (4). 1,2-Dimethylcyclopropene was synthesized by methylation of 1-methylcyclopropene, which was obtained by the method of Fisher and Applequist.[31] 1-Methylcyclopropene prepared from 44.4 g (1.14 mol) of sodium amide and 100 mL (1.04 mol) of methacryl chloride was dissolved in 40 mL of liquid ammonia at −78 °C and to this solution was added 1,2-dimethoxyethane (40 mL) and methyl iodide (35.0 mL, 0.56 mol). Sodium amide prepared freshly from sodium (11 g, 0.513 mol) in liquid NH_3 (170 mL) in a separate flask was transferred to this solution through Teflon tubing. The reaction mixture was stirred at the boiling point of ammonia for 30 min and then cooled to −78 °C. To this was added water (100 mL) and carbon tetrachloride (100 mL), and the temperature of the solution was gradually raised to room temperature with stirring. The carbon tetrachloride solution was separated and the water layer was again extracted with 50 mL of carbon tetrachloride. The combined organic layer was washed with water (50 mL × 4) and dried with anhydrous $MgSO_4$. ^1H NMR analysis of the solution with benzene as an internal standard showed the formation of 1,2-dimethylcyclopropene (263 mmol, 26%), 1-methylcyclopropene (75 mmol, 70%), and methylenecyclopropane (62 mmol, 6%).[32] Distillation of this solution gave a carbon tetrachloride solution of 1,2-dimethylcyclopropene (142 mmol) and methylenecyclopropane (27 mmol) (by NMR). A carbon tetrachloride solution (150 mL) of thiocyanogen (42.7 mmol) was cooled to −20 °C and irradiated by a 100-W Hg lamp. After 5 min, the above solution of 1,2-dimethylcyclopropene (26 mmol) was added dropwise over 15 min and then the mixture was irradiated for an additional 1.5 h. After filtration of insoluble yellow solid, the solvent was evaporated from the filtrate to give a yellow oil with an unplesant smell. Dry column chromatography (alumina, hexane–ether 2:1) of the oil gave a 1:1 mixture (8.3 mmol, 32%) of *cis*- (**5**) and *trans*-1,2-dimethyl-1,2-dithiocyanatocyclopropane (**6**) and *cis*-1,2-dimethyl-1,2-diisothiocyanatocyclopropane (**7**) (1.7 mmol, 7%). Although separation of **5** and **6** was possible by preparative TLC (alumina, hexane–ether 3:1), it resulted in extensive loss of the samples probably because of decomposition. Therefore, the mixture of **5** and **6** was used for the next step. A THF solution (30 mL) of the 1:1 mixture of **5** and **6** (1.162 g, 6.32 mmol) was added to the THF solution (20 mL) of lithium aluminum hydride (1.48 g, 40.0 mmol). After 1 h of reflux, the solution was cooled to 0 °C and to this was added slowly ethyl acetate (20 mL) to destroy excess hydride. To the solution again heated to reflux was added a THF solution (100 mL) of diiodomethane (2.0 mL, 24.8 mmol) over 2.5 h and the mixture was refluxed for an additional 1 h. After the usual workup, the products were purified by DCC (SiO_2, CCl_4) to give **4** (434 mg, 94% from **5**) as a yellow oil, which was further purified by bulb-to-bulb distillation (80 °C at 25 mmHg).

5: a yellow oil; ^1H NMR δ 1.44 (ABq, 2 H, $\Delta\delta$ = 13 Hz, J = 7.5 Hz), 1.82 (s, 6 H); IR (neat) 2160 cm^{-1} (SCN); MS, *m/e* 126 (47%, M^+ − SCN), 67 (49), 59 (100), 41 (56), 39 (30).

6: white crystals, mp 50.5–52.0 °C (hexane–ether); ^1H NMR δ 1.40 (s, 2 H), 2.00 (s, 6 H); IR (neat) 2160 cm^{-1} (SCN); MS, *m/e* 126 (86, M^+ − SCN), 67 (70) 59 (100), 41 (57), 39 (41).

7: a yellow oil; ^1H NMR δ 1.27 (ABq, 2 H, $\Delta\delta$ = 9 Hz, J = 7 Hz), 1.79 (s, 6 H); IR (neat) 2100 cm^{-1} (br) (NCS); MS, *m/e* 184 (M^+, 59), 126 (63), 67 (65), 59 (49), 41 (100), 39 (63).

4: ^1H NMR δ 0.87 (ABq, 2 H, $\Delta\delta$ = 27.5 Hz, J = 7.4 Hz), 1.53 (s, 6 H), 3.64 (ABq, 2 H, $\Delta\delta$ = 9 Hz, J = 12 Hz); ^{13}C NMR δ 17.53, 23.22, 30.94, 40.91; IR (neat) 2960, 2930, 2870 (sh), 1465 (sh), 1450, 1385, 1220, 1155, 1065, 1025, 730 cm^{-1}; MS, *m/e* 146 (M^+, 67), 131 (65), 100 (61), 99 (33), 85 (98), 59 (100); HRMS 146.0234 (calcd for $C_6H_{10}S_2$ 146.0224).

8,8-Dideuterio-7,9-dithiatricyclo[4.3.1.0^{1,6}]deca-2,4-diene (3-d_2) and 3,3-Dideuterio-1,5-dimethyl-2,4-dithiabicyclo[3.1.0]hexane (4-d_2). **3-d_2** and **4-d_2** were synthesized in a similar way to that of 3[9c] and **4** with diiodomethane-d_2 (CD_2I_2 98.8%, $CHDI_2$ 1.2% by MS), which was obtained by the method of Winstein.[33]

3-d_2: ^1H NMR δ 0.54 (d, J = 6 Hz, 1 H), 2.25 (d, J = 6 Hz, 1 H), 5.90–6.70 (m, 4 H); HRMS 170.0205 (calcd for $C_8H_6D_2S_2$ 170.0193).

4-d_2: ^1H NMR δ (CCl_4) 0.92 (ABq, 2 H, $\Delta\delta$ = 26 Hz, J = 7 Hz), 1.49 (s, 6 H); IR (neat) 2970, 2930, 2870, 1465, 1450, 1390, 1220, 1150, 1025, 920, 675 cm^{-1}; HRMS 148.0359 (calcd for $C_6H_8D_2S_2$ 148.0349).

Reactions of Carbanions 8 and 9 with Electrophiles. General Procedure. To a THF solution (4–10 mL) of **3** or **4** (0.4–10 mmol) was added at −78 °C butyllithium (hexane solution, 1.1 equiv). After the mixture was stirred at this temperature for 10 min, HMPA (1.2 equiv) and an electrophile (1.2 equiv) were added by a syringe (in the reaction with DCl an acetyl chloride solution of excess D_2O was used). The solution was stirred for an additional 10 min at −78 °C and the temperature was gradually raised to room temperature where stirring was continued for 1 h. After evaporation of THF, the products were partitioned between water and dichloromethane. The aqueous layer was extracted with dichloromethane and the combined organic extracts were dried over $MgSO_4$, filtered, and evaporated in vacuo. The crude products thus obtained were purifed by Florisil (for the reaction products with **3**) or silica gel (for the reaction products with **4**) chromatography. The products from **3** were sometimes extensively decomposed when silica gel was used.

In the reactions of **3** and **4** with methyl iodide the effect of added HMPA was studied. Either in the complete absence or in the presence of 20 equiv of HMPA, **3** gave **10bt** exclusively (by ^1H NMR) in 95 or 97% yield, respectively. Similarly **4** afforded only **11bt** in 60 or 71% yield, respectively.

10 and **11** were each obtained as a colorless or pale yellow oil.

10at: ^1H NMR δ 0.54 (d, J = 6 Hz, 1 H), 2.25 (d, J = 6 Hz, 1 H), 3.65 (t, J = 1.8 Hz, 1 H), 5.90–6.60 (m, 4 H); HRMS 169.0115 (calcd for $C_8H_7DS_2$ 169.0130).

10ac: ^1H NMR δ 0.54 (d, J = 6 Hz, 1 H), 2.25 (d, J = 6 Hz, 1 H), 4.15 (t, J = 1.8 Hz, 1 H), 5.90–6.60 (m, 4 H); HRMS 169.0135 (calcd for $C_8H_7DS_2$ 169.0130).

11at: ^1H NMR δ (CCl_4) 0.93 (ABq, 2 H, $\Delta\delta$ = 37 Hz, J = 7.2 Hz), 1.50 (s, 6 H), 3.48 (t, 1 H, J = 1.5 Hz); IR (neat) 2960, 2930, 2860, 2855, 1460, 1260 cm^{-1}; HRMS 147.0289 (calcd for $C_6H_9DS_2$ 147.0287).

11ac: ^1H NMR δ (CCl_4) 0.93 (ABq, 2 H, J = 7.2 Hz, $\Delta\delta$ = 39.8 Hz), 1.53 (s, 6 H), 3.66 (t, 1 H, J = 1.5 Hz); IR (neat) 2970, 2730, 2870, 1450, 1385, 1150, 1070, 1020, 850 cm^{-1}; HRMS 147.0295 (calcd for $C_6H_9DS_2$ 147.0287).

10bt: ^1H NMR δ 0.64 (d, J = 5.0 Hz, 1 H), 1.64 (d, J = 7.0 Hz, 3 H), 2.48 (d, J = 5.0 Hz, 1 H), 4.55 (q, J = 7.0 Hz, 1 H), 5.80–6.60 (m,

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4 H); IR (neat) 3080, 3025, 2920, 1700, 1580, 1540, 1440, 1420, 1370, 1280, 1090, 1050 cm^{-1}; MS (*m/e*) 182 (M$^+$, 62), 167 (100), 122 (49), 121 (57); HRMS 182.0194 (calcd for $C_9H_{10}S_2$ 182.0222).

11bt: ^{1}H NMR δ (CCl_4) 1.08 (ABq, 2 H, $\Delta\delta$ = 43 Hz, J = 6.5 Hz), 1.64 (s, 6 H), 1.67 (d, 3 H), 4.07 q, 1 H, J = 6.5 Hz); IR (neat) 2970, 2940, 2870, 1700, 1455, 1385, 1150, 1125, 1080 cm^1; MS, *m/e* 160 (M$^+$, 43), 145 (22), 100 (66), 99 (66), 85 (85), 59 (100); HRMS 160.0370 (calcd for $C_7H_{12}S_2$ 160.0380).

10ct: ^{1}H NMR δ (CCl_4) 0.70 (d, J = 4.5 Hz, 1 H), 2.53 (d, J = 4.5 Hz, 1 H), 3.00 (d, J = 7.5 Hz, 2 H), 4.43 (t, J = 7.5 Hz, 1 H), 5.80–6.60 (m, 5H); IR (neat) 3080, 3060, 2920, 1700, 1600, 1585, 1550, 1495, 1455, 1435, 1380, 1265, 1220, 1075 cm^{-1}; MS, *m/e* 258 (M$^+$, 11), 167 (100), 121 (20), 91 (25); HRMS 258.0537 (calcd for $C_{15}H_{14}S_2$ 258.0537).

11ct: ^{1}H NMR δ (CCl_4) 1.00 (ABq, 2 H, J = 6.3 Hz, $\Delta\delta$ = 51.3 Hz), 1.49 (s, 6 H), 3.06 (d, 2 H, J = 7 Hz), 4.21 (t, 1 H, J = 7 Hz); ^{13}C NMR δ 128.54, 127.03, 52.34, 41.77, 39.55, 26.71, 18.29, 26.71, 18.29; IR (neat) 3090, 3030, 2960, 2930, 2870, 1695, 1680, 1605, 1495, 1455, 1385, 1150, 1080, 1030, 740, 705 cm^{-1}; MS, *m/e* 236 (M$^+$, 3), 145 (100), 100 (16), 99 (16), 91 (17), 85 (30), 59 (25); HRMS 236.0727 (calcd for $C_{13}H_{16}S_2$ 236.0694).

10dt: ^{1}H NMR δ 0.18 (s, 9 H), 0.37 (d, J = 6.0 Hz, 1 H), 2.10 (d, J = 6.0 Hz, 1 H), 3.26 (s, 1 H), 5.90–6.60 (m, 4 H); IR (neat) 3065, 3030, 2960, 2895, 1655, 1545, 1410, 1375, 1255, 1170, 1120, 1085, 1045 cm^{-1}; MS, *m/e* 240 (M$^+$, 13), 167 (38), 41 (100); HRMS 240.0482 (calcd for $C_{11}H_{16}SiS_2$ 240.0462).

11dt: ^{1}H NMR δ 0.15 (s, 9 H), 0.90 (ABq, 2 H, $\Delta\delta$ = 45 Hz, J = 6.3 Hz), 1.49 (s, 6 H), 3.17 (s, 1 H); ^{13}C NMR δ −2.00, 17.15, 20.67, 32.89, 42.10; IR (neat) 2960, 2730, 1255, 1150, 865, 845 cm^{-1}; MS, *m/e* 218 (M$^+$, 6), 145 (25), 113 (97), 100 (31), 99 (25), 85 (41), 73 (100), 59 (60); HMRS 218.0627 (calcd for $C_9H_{18}S_2Si$ 218.0619).

10et: ^{1}H NMR δ 0.67 (d, J = 4.8 Hz, 1 H), 2.48 (d, J = 4.8 Hz, 1 H), 2.53 (t, J = 7.2 Hz, 2 H), 4.36 (t, J = 7.2 Hz, 1 H), 4.80–6.50 (m, 7 H); IR (neat) 3070, 3030, 2970, 1635, 1575, 1540, 1425, 1370, 1255, 1215, 1090, 1045, 980, 915, 710, 660, 640 cm^{-1}; MS, *m/e* 208 (M$^+$, 11), 167 (100), 91 (25); HRMS 208.0349 (calcd for $C_{11}H_{12}S_2$ 208.0379).

10ft: ^{1}H NMR δ 0.77 (d, J = 4.5 Hz, 1 H), 2.58 (d, J = 4.5 Hz, 1 H), 3.37 (s, 3 H), 3.40 (d, J = 5.4 Hz, 2 H), 4.42 (t, J = 5.4 Hz, 1 H), 5.7–6.5 (m, 4 H); ^{13}C NMR δ 58.92, 65.88, 75.63, 118.63, 130.28; IR (neat) 3030, 2980, 2925, 2880, 2820, 1450, 1190, 1115, 1095, 735, 715 cm^{-1}; MS, *m/*e 212 (M$^+$, 17), 167 (100), 135 (17), 134 (23), 123 (20), 121 (31), 91 (36), 77 (24), 45 (57); HRMS 212.0358 (calcd for $C_{10}H_{12}OS_2$ 212.0328).

10gt: ^{1}H NMR δ 0.73 (d, J = 4.0 Hz, 1 H), 2.55 (d, J = 4.0 Hz, 1 H), 3.10 (br s, 1 H), 4.32 (d, J = 9.0 Hz, 1 H), 4.44 (d, J = 9.0 Hz, 1 H), 5.80–6.50 (m, 4 H), 7.25 (m, 5 H); IR (neat) 3450, 3060, 3030, 2980, 1645, 1615, 1580, 1490, 1450, 1380, 1230, 1190, 1090, 1040 cm^{-1}; MS, *m/e* 274 (M$^+$, 3), 167 (35), 105 (91), 91 (34), 86 (41), 84 (69), 77 (100); HRMS 274.0506 (calcd for $C_{15}H_{14}OS_2$ 274.0486).

11gt: ^{1}H NMR δ (CCl_4) 1.12 (ABq, $\Delta\delta$ = 50 Hz, J = 4.5 Hz, 2 H), 1.49 (s, 6 H), 2.86 (br s, 1 H), 4.25 (d, J = 7.2 Hz, 1 H), 4.67 (d, J = 7.2 Hz, 1 H), 7.15–7.45 (m, 5 H); IR (neat) 3450, 3070, 3040, 1490, 1455, 1385, 1190, 1110, 1040, 710, 740, 700 cm^{-1}; MS *m/e* 145 (64), 131 (26), 167 (100), 99 (17), 91 (14), 79 (45), 77 (44), 59 (24); HMRS 252.0626 (calcd for $C_{13}H_{16}OS_2$ 252.0641).

10ht: ^{1}H NMR δ 0.85 (d, J = 4.5 Hz, 1 H), 2.66 (d, J = 4.5 Hz, 1 H), 3.65 (s, 3 H), 4.74 (s, 1 H), 5.80–6.60 (m, 4 H); ^{13}C NMR δ 39.85, 51.06, 52.58, 62.88, 118.73, 129.38, 170.35; IR (neat) 1746, 1724, 1430, 1280, 1150, 710 cm^{-1}; MS, *m/e* 226 (M$^+$, 21), 210 (8), 169 (10), 168 (12), 167 (100), 134 (15), 123 (15), 121 (15), 91 (24), 57 (21), 55 (19), 45 (19); HRMS 226.0133 (calcd for $C_{10}H_{10}O_2S_2$ 226.0123).

10hc: ^{1}H NMR δ 0.92 (d, J = 5.5 Hz, 1 H), 2.56 (d, J = 5.5 Hz, 1 H), 3.77 (s, 3 H), 5.33 (s, 1 H), 5.85–6.50 (m, 4 H); ^{13}C NMR δ 27.96, 49.38, 53.39, 59.39, 119.98, 128.27, 170.69; IR (neat) 1740, 1430, 1280, 1160, 710 cm^{-1}; MS, *m/e* 226 (M$^+$, 30), 217 (7), 169 (12), 168 (13), 167 (100), 134 (19), 123 (16), 121 (20), 77 (17), 55 (19), 45 (25); HRMS 226.0123 (calcd for $C_{10}H_{10}O_2S_2$ 226.0123).

11ht: ^{1}H NMR δ (CCl_4) 1.43 (ABq, $\Delta\delta$ = 55.8 Hz, J = 4.5 Hz, 2 H), 1.60 (s, 6 H), 3.73 (s, 3 H), 4.44 (s, 1 H); ^{13}C NMR δ 20.16, 41.23, 44.97, 52.93, 57.08, 171.05; IR (neat) 2950, 2930, 1740, 1680, 1435, 1285, 1215, 1145, 1020 cm^{-1}; MS, *m/e* 204 (M$^+$, 4), 145 (64), 131 (81), 100 (17), 99 (24), 85 (52), 59 (100); HRMS 204.0285 (calcd fo $C_8H_{12}O_2S_2$ 204.0279).

11hc: ^{1}H NMR δ 0.81 (d, J = 6.3 Hz, 1 H), 1.52 (s, 6 H), 1.86 (d, J = 6.3 Hz, 1 H), 3.70 (s, 3 H), 4.70 (s, 1 H); MS, *m/e* 204 (M$^+$, 7), 145 (46), 131 (100), 100 (16), 99 (25), 85 (53), 59 (68); HRMS 204.0292 (calcd for $C_8H_{12}O_2S_2$ 204.0279).

Conversion of 10h into 10f. A THF solution (10 mL) of **10ht** (68 mg, 0.30 mmol) was added to an ethereal solution (10 mL) of lithium aluminum hydride (50 mg) at 0 °C. The solution was stirred for 2 h at room temperature and quenched with 6 M HCl. After the usual workup, **10it** was obtained quantitatively. Since it was homogeneous by TLC, it was used for methylation without further purification. ^{1}H NMR δ 0.77 (d, J = 4.5 Hz, 1 H), 2.64 (d, J = 4.5 Hz, 1 H), 2.58 (br s, 1 H), 3.46 (d, J = 7.2 Hz, 2 H), 4.39 (t, J = 7.2 Hz, 1 H), 5.75–6.60 (m, 4 H); IR (neat) 3410, 2920, 2860, 1090, 1055, 1020, 735, 715 cm^{-1}; MS, *m/e* 198 (M$^+$, 9), 167 (100), 123 (20), 121 (25), 91 (35), 31 (59). A THF solution (5 mL) of **10it** obtained above was added to a suspension of sodium hydride (50 mg, 1.25 mmol) in THF. To this was added methyl iodide (0.20 mL, 3.21 mmol) and the solution was stirred overnight at room temperature. After the usual workup, the crude product was puirified by Florisil chromatography (pentane–dichloromethane 3:1) to give **10ft** (46 mg, 72%) as a yellow oil whose ^{1}H NMR spectram was identical with that of the compound obtained from **3**, butyllithium, and methoxymethyl chloride (vide infra).

Conversion of **10hc** into **10fc** was similarly conducted; the yields of **10ic** from **10hc** and **10fc** from **10ic** were 94 and 55%, respectively.

10ic: ^{1}H NMR δ 0.70 (d, J = 4.8 Hz, 1 H), 2.30 (d, J = 4.8 Hz, 1 H), 2.60 (br s, 1 H), 3.63 (d, J = 6.0 Hz, 2 H), 5.28 (t, J = 6.0 Hz, 1 H), 5.70–6.50 (m, 4 H); IR (neat) 3390, 2950, 2925, 2860, 1055 cm^{-1}. **10fc**: ^{1}H NMR δ 0.78 (d, J = 5.4 Hz, 1 H), 2.55 (d, J = 5.4 Hz, 1 H), 3.37 (s, 3 H), 3.55 (d, J = 7.2 Hz, 2 H), 5.60 (t, J = 7.2 Hz, 1 H), 5.80–6.50 (m, 4 H); IR (neat) 3390, 2950, 2925, 2860, 1055 cm^{-1}; HRMS 153.1208 (calcd for $C_{10}H_{12}OS_2$ 153.1206).

Reactions of Lithiated 10at and 10ac with Methyl Iodide. The reactions were carried out in a similar way to that described in the General Procedure section of the reactions of **8** with electrophiles. Deuterium analysis was performed at 15 eV.

Inversion of 10ht to 10hc. Butyllithium (1.50 mmol) in hexane was added at −78 °C to a THF solution (50 mL) of **10ht** (310 mg, 1.37 mmol) containing 0.3 mL of HMPA. After being stirred for 50 min at the same temperature, the solution was rapidly quenched with THF (5 mL) containing 1 mL of concentrated HCl and the temperature was gradually raised to room temperature. After the usual workup, the crude product was analyzed by ^{1}H NMR, showing the complete absence of **10ht**. Purification by silica gel chromatography (hexane–benzene 1:1) gave **10hc** (228 mg, 74%).

Inversion of 11ht to 11hc. A THF solution (20 mL) of **11ht** (36 mg, 0.173 mmol) containing 0.1 mL of HMPA was treated with butyllithium (0.19 mmol) at −78 °C. After being stirred for 10 min at the same temperature, the solution was quenched with a THF solution (5 mL) of concentrated HCl (0.2 mL) and gradually warmed to room temperature. After the usual workup, the crude reaction mixture was chromatographed to collect fractions expected for **11ht** and **11hc**. They were shown to be a 99.1:0.9 mixture (28 mg, 79%) of **11ht** and **11hc** by gas chromatography (QF-1, column temperature 120 °C).

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