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STUDIES ON GENERATION OF REACTIVE COMPOUNDS INVOLVING CARBON-CHALCOGEN MULTIPLE BONDS

(炭素・カルコゲン多重結合を有する
活性化学種に関する研究)

MASAHITO SEGI

1989

Preface

The studies presented in this thesis have been carried out under the guidance of Professor Noboru Sonoda at the Department of Applied Chemistry, Faculty of Engineering, Osaka University for one year, from 1986 to 1987, and at the Department of Chemistry and Chemical Engineering, Faculty of Technology, Kanazawa University for the following two years, from 1987 to 1989.

The thesis is concerned with generation and reaction of reactive compounds involving carbon-chalcogen multiple bonds.

Kodatsuno, Kanazawa
June 1989

Masahito Segi

List of Publications

The contents of this thesis are composed of the following papers.

1. Direct Conversion of Aldehydes to Seleno- and Thioaldehydes
   Segi, M.; Nakajima, T.; Suga, S.; Murai, S.; Ryu, I.; Ogawa, A.; Sonoda, N.
   J. Am. Chem. Soc. 1988, 110, 1976.

2. Intramolecular Diels-Alder Reaction of Selenoaldehydes
   Segi, M.; Takahashi, M.; Nakajima, T.; Suga, S.; Murai, S.; Sonoda, N.
   Tetrahedron Lett. 1988, 29, 6965.

3. Novel Route to Selenoketones from Ketones by the Use of Bis(dimethylaluminum) Selenide
   Segi, M.; Koyama, T.; Nakajima, T.; Suga, S.; Murai, S.; Sonoda, N.
   Tetrahedron Lett. 1989, 30, 2095.

4. A Convenient One-pot Synthesis of Unsymmetrical Selenium Compounds Using Bis(trimethylsilyl) Selenide
   Segi, M.; Kato, M.; Nakajima, T.; Suga, S.; Sonoda, N.
   Chem. Lett. 1989, 1009.

5. Intramolecular Diels-Alder Reaction of Thioaldehydes
   Segi, M.; Takahashi, M.; Nakajima, T.; Suga, S.;
   Sonoda, N.
   Synth. Commun. in press.

6. Telluroaldehydes and Telluroketones
   Segi, M.; Koyama, T.; Takata, Y.; Nakajima, T.; Suga, S.
   J. Am. Chem. Soc. submitted.

7. Preparation and Reactions of Thioaldehydes
   Segi, M.; Saito, H.; Komiyama, N.; Nakajima, T.; Suga, S.;
   Sonoda, N.
   to be published.

List of Other Publications

1. Comparison of Lewis Acids as Catalyst for the Alkylation of Benzene with s-Butyl Chloride
   Segi, M.; Nakajima, T.; Suga, S.
   Bull. Chem. Soc. Jpn. 1980, <u>53</u>, 1465.

2. The Participation Effect of Halogen Atoms in Stereospecific Friedel-Crafts Alkylations
   Masuda, S.; Segi, M.; Nakajima, T.; Suga, S.
   J. Chem. Soc., Chem. Commun. <u>1980</u>, 86.

3. Stereochemistry of Friedel-Crafts Alkylation of Benzene with Optically Active 2-Chlorobutane
   Suga, S.; Segi, M.; Nakajima, T.
   Bull. Chem. Soc. Jpn. 1981, 54, 3611.

4. Stereochemistry of Friedel-Crafts Reaction of Benzene with Optically Active 2-Methyloxetane
   Segi, M.; Takebe, M.; Masuda, S.; Nakajima, T.; Suga, S.
   Bull. Chem. Soc. Jpn. 1982, 55, 167.

5. Preparation of Optically Active Phosphine Oxides by Regioselective Cleavage of Cyclic Phenylphosphonite with Alkyl Halides
   Segi, M.; Nakamura, Y.; Nakajima, T.; Suga, S.
   Chem. Lett. 1983, 913.

6. Reaction of 1-Trimethylsilylcyclopropyllithium Derivatives with Dichloromethyl Methyl Ether. A Novel Synthesis of Cyclopropyl Silyl Ketones
   Nakajima, T.; Ohno, K.; Tanabe, M.; Segi, M.; Suga, S.
   Chem. Lett. 1986, 177.

7. Ring Opening and Enlargement of Cyclopropyl Trimethylsilyl Ketones by Acids
   Nakajima, T.; Miyaji, H.; Segi, M.; Suga, S.
   Chem. Lett. 1986, 181.

8. Asymmetric Synthesis of Phosphine Oxides with the Arbuzov Reaction
   Kato, T.; Kobayashi, K.; Masuda, S.; Segi, M.; Nakajima, T.; Suga, S.
   Chem. Lett. 1987, 1915.

Contents

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Chapter 5. A New Route to Telluro-aldehydes and -ketones Using Bis(dimethylaluminum) Telluride

General Introduction

The chemistry of the carbonyl group is well known as one of the cornerstones of organic synthesis, and that of the thiocarbonyl group has recently become much more familiar to the practising organic chemist. The corresponding selenium and tellurium compounds are generally considered to be exotic and perhaps out of the mainstream of organic chemistry because of their high reactivity and difficulty of preparation. However, such reactive molecules involving carbon-chalcogen multiple bonds have been of current interest in their structure and reactivity.[1]

The utmost important problem in the chemistry of chalcogeno-carbonyl compounds is to find a practical preparative method. Synthetically, the most useful methods are those that directly convert the more readily available carbonyl compounds into the corresponding chalcogeno-carbonyl compounds. On the other hand, it is well recognized that silicon and aluminum are excellent oxygenophiles, and addition and elimination reactions of these organometallic compounds with many accepter molecules have been studied.[2] It may be accordingly expected that carbon-chalcogen double bonds are construct by utilizing the tendency of relatively unstable R_3M-Y-MR_3 compounds to change into more stable R_3M-O-MR_3 compounds. The prime objective of the present research is to develop new chalcogenating reagents and to establish a general and efficient method for the generation of reactive chalcogeno-carbonyl compounds.

This thesis consists of five chapters. Chapter 1 deals with direct conversion of aldehydes to selenoaldehydes using bis(trimethylsilyl) selenide or hexamethylcyclotrisilaselenane as a selenating reagent. In this method, catalytic amounts of base such as n-BuLi is essential. A reaction mechanism with a catalytic cycle will be described. Further, application to synthesis of unsymmetrical selenium compounds using bis(trimethylsilyl) selenide is also described. Chapter 2 is concerned with novel method of selenoketone generation by the use of a new selenating reagent, bis(dimethylaluminum) selenide. A useful method for the preparation of this new reagent will be demonstrated. In chapter 3 is delt synthesis of thioaldehydes using bis(trimethylsilyl) sulfide under base-catalyzed condition. Inter- or intra-molecular Diels-Alder reaction and Wittig type reaction of thioaldehydes obtained by the present method are described. Chapter 4 deals with synthesis and Diels-Alder reaction of thioketones. The study on the stereo- and regiochemistry of cycloaddition of thioketones with a 1,3-diene will be also described. Chapter 5 refers to the first generation and trapping of telluroaldehydes and telluroketones using a new tellurating reagent, bis(dimethylaluminum) telluride.

References

(1) (a) Organic Compounds of Sulphur, Selenium, and Tellurium Specialist Periodical Reports; The Chemical Society: London, 1970-1981; Vols. 1-6. (b) Magnus, P. D. Comprehensive Organic Chemistry; Barton, D. H. R.; Ollis, W. D., Ed.; Pergamon Press: Oxford, 1979; Vol. 3, 489. (c) The Chemistry of Organic Selenium and Tellurium Compounds; Patai, S.; Rappoport, Z., Ed.; John Wiley & Sons: New York, 1985 and 1987; Vols. 1-2. (d) Paulmier, C. Selenium Reagents and Intermediates in Organic Synthesis; Baldwin, J. E., Ed.; Pergamon Press: Oxford, 1986. (e) Organoselenium Chemistry; Liotta, D., Ed.; John Wiley & Sons: New York, 1987. (f) Krief, A.; Hevesi, L. Organoselenium Chemistry I; Springer-Verlag: Berlin, 1988. (g) Boger, D. L.; Weinreb, S. M. Hetero Diels-Alder Methodology in Organic Synthesis; Academic Press: New York, 1987, 120. (h) Reviews on Heteroatom Chemistry; Oae, S., Ed.; Myu: Tokyo, 1988.

(2) (a) Lappert, M. F.; Prokai, B. Adv. Organometal. Chem.; Academic Press: New York, 1967; Vol. 5, 225. (b) Colvin, E. W. Silicon Reagents in Organic Synthesis; Academic Press: New York, 1988.

Chapter 1. Generation and Cycloaddition Reactions of Selenoaldehydes

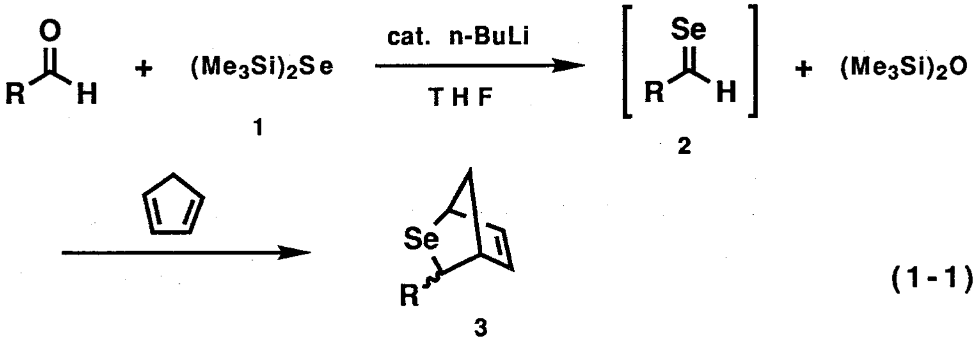
1-1 Introduction

The chemistry of molecules having unstable carbon-heteroatom multiple bonds is of great importance and interest. Until quite recently, the chemistry of selenoaldehydes has remained almost undeveloped because of their high reactivity and difficulty of preparation.[1] The isolation of several selenoaldehydes stabilized by electron-donating groups or by coordination to the transition metals has been reported. Reid et al.[2] first isolated several stable selenoaldehydes with vinylogous selenoformamide structures, their stability being derived from resonance delocalization of nitrogen lone pair electrons onto selenium. Fischer et al.[3a,c] have reported the synthesis of selenobenzaldehydes stabilized by coordination to chromium and tungsten. Though monomeric selenoaldehydes have not been isolated as free species without resort to such stabilizations as yet, they have been known to react with 1,3-dienes to give the corresponding Diels-Alder adducts[3b-8] or to isomerize to benzoselenane.[9] The utmost important problem in selenoaldehyde chemistry is still to find a practical preparative method. The most efficient method for selenoaldehydes known to date would be that of Krafft and Meinke, who reported in 1986 the generation of selenoaldehydes by β-elimination of silicon and cyano moieties from, for example, α-silyl-α-(cyanoselenenyl)-toluene [$Me_3SiCH(Ph)SeCN$].[4a] This precursor, however, should be prepared in one or two steps from aldehydes.

This chapter describes very simple methods which allow the direct conversion of aldehydes to selenoaldehydes and Diels-Alder reactions of selenoaldehydes with 1,3-dienes.

1-2 Direct Conversion of Aldehydes to Selenoaldehydes Using Bis(trimethylsilyl) Selenide under Base-catalyzed Condition

It seemed that for the conversion of relatively stable carbon-oxygen double bond to such an unstable bond as selenium-carbon double bond, a sufficiently large driving force should be supplied by the concomitant change of the reagent used, and any byproducts or reagents should not react with the labile product, selenoaldehydes. It is considered that the seemingly large energy difference between bis(trimethylsilyl) selenide ($Me_3SiSeSiMe_3$, **1**)[10] and disiloxane ($Me_3SiOSiMe_3$)[11] serves as the driving force of the desired transformation. Thus the reaction of aldehydes with **1** extensively with respect to the catalysts and reaction conditions was investigated. Among various candidates including ZnI_2, $TiCl_4$, n-BuLi, R_3N, and R_3P examined for the catalyst, only n-BuLi has met with success. The reaction was carried out in the presence of cyclopentadiene which is known as a good trapping agent for selenoaldehydes[3b-8] (eq. 1-1). In this new method, disilyl selenide 1 works not only for the introduction of a selenium atom but also for removal of oxygen.



(1-1)

The representative examples are summarized in Table 1-1.[15] These satisfactory yields of cycloadducts 3 imply that selenoaldehyde generation occurs efficiently under this base-catalyzed condition except for entry 6. Use of 5-10 mol% butyllithium in a highly diluted solution (0.03 M solution of 1 in THF) suppressed the undesired reactions.[16] The Diels-Alder adducts with cyclopentadiene yielded a mixture of endo and exo isomers, with the former predominating in all cases. Endo and exo isomer ratios were determined by integration of ^1H-NMR signals. The observed endo stereopreference would be explained by positive frontier orbital interactions (secondary orbital overlap) for the aromatic selenoaldehydes and steric interac-

Table 1-1. Generation and Reaction of Selenoaldehydes 2 with Cyclopentadiene

entry	RCHO, R	reaction condn temp (°C)	reaction condn time (h)	isolated yield of 3 (%)	isomer ratio endo:exo[a]
1	C_6H_5	25	7	73	4 : 1
2	4-Cl-C_6H_4	25	3	72	4 : 1
3	2-furyl	15	3	85	2 : 1
4	n-C_3H_7	40	6	71	7 : 1
5	i-C_3H_7	40	6	81	10 : 1
6	t-C_4H_9	60	4	45	>20 : 1

[a] Determined by ^{1}H-NMR .

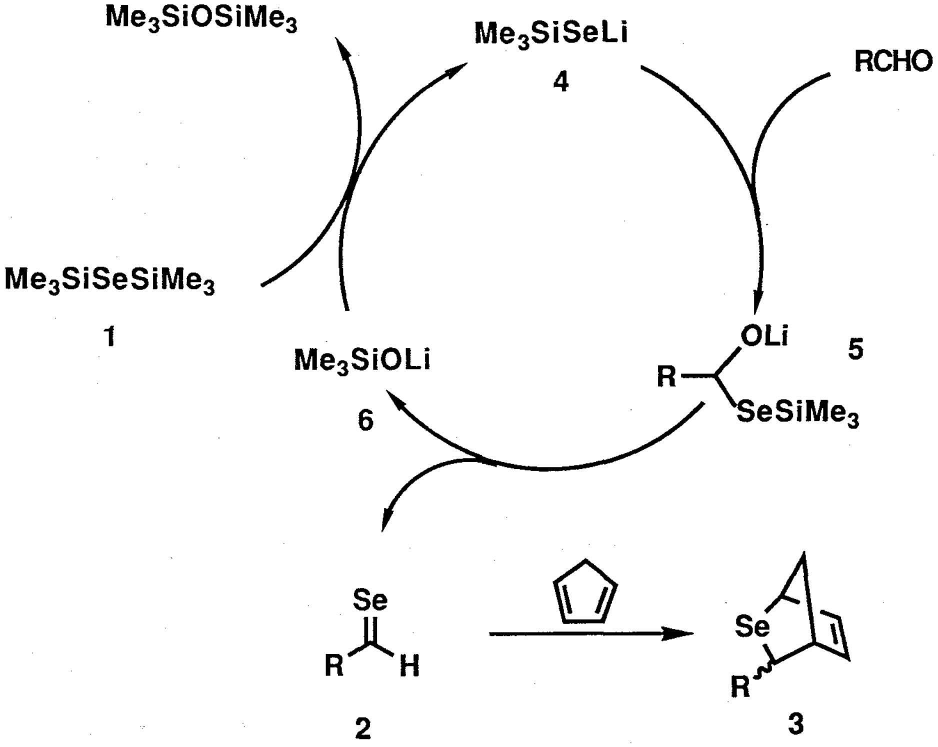
tions between the substituent R on aldehydes and methylene protons in cyclopentadiene for the aliphatic selenoaldehydes in the endo transition state.[17] These results are consistent with those reported by Krafft and Meinke.[4]

A catalytic cycle proposed for selenoaldehyde formation was illustrated in Scheme 1-1. Lithium trimethylsilylselenide ($Me_3SiSeLi$, 4), generated in situ from the treatment of 1 with butyllithium, attacks the carbonyl carbon of aldehyde to give the corresponding unstable intermediate 5, which then undergoes elimination of (trimethylsiloxy)lithium (Me_3SiOLi, 6) probably via the Peterson-type mechanism[18] to give a selenoaldehyde 2 that is immediately trapped by cyclopentadiene to give the observed adduct 3. The eliminated 6 reacts with 1 to give the siloxane and regenerates the active catalyst 4.

It appears that the initial addition of the $Me_3SiSeLi$ to the carbonyl is the rate-limiting step, since the 4-chlorobenzaldehyde reacts more than twice as fast as benzaldehyde. This possibility is also substantiated by the higher temperatures required for reactions of the sterically encumbered pivalaldehyde. The cycloaddition step cannot be the slow step since Krafft's procedure requires 2 h at 0 °C for selenobenzaldehyde,[4a] compared with 7 h at 25 °C in this work.

The described method opens a new route to the generation of selenoaldehydes and will permit further studies of the reactivity of those exotic molecules.

$$\mathrm{Me_3SiSeSiMe_3} \quad + \quad \text{n-BuLi} \longrightarrow \mathrm{Me_3SiSeLi} \quad + \quad \text{n-BuSiMe}_3$$

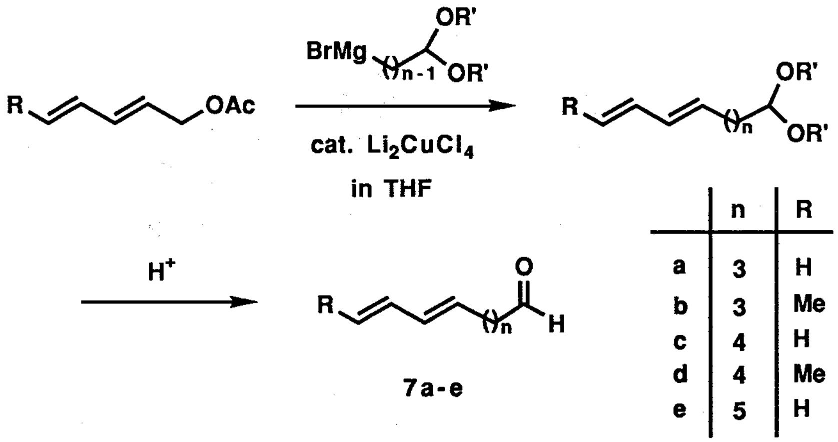


Scheme 1-1

1-3 Intramolecular Diels-Alder Reaction of Selenoaldehydes

Intramolecular Diels-Alder reaction of selenoaldehydes with dienes has not been reported so far probably because of the difficulty in the generation of the required selenoaldehyde having a diene function. Very recently the sulfur analogue has been reported to undergo intramolecular Diels-Alder reaction.[19,20] In this section, the first example of intramolecular Diels-Alder reaction of selenoaldehydes is repesented.

Dienals **7** used for this study were synthesized by a modified method of Roush's[21] (eq. 1-2). Copper-catalyzed cross-coupling of trans-2,4-pentadienyl acetate (R=H) or trans,trans-2,4-hexadienyl acetate (R=Me) with Grignard reagent derived from protected bromoaldehyde having an appropriate chain length (n=3-5) followed by deprotection (acetic acid) gave the corresponding dienals **7** in 28-45% yields.

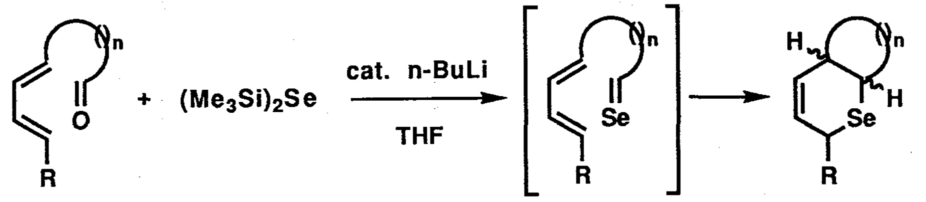


7a-e

	n	R
a	3	H
b	3	Me
c	4	H
d	4	Me
e	5	H

(1-2)

The reaction of dienals 7 and bis(trimethylsilyl) selenide 1[10] in the presence of a catalytic amount of butyllithium in THF gave selenoaldehydes 8 which underwent rapid and efficient intramolecular cycloaddition to yield bicyclic adducts 9, as outlined in eq. 1-3.



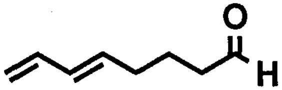
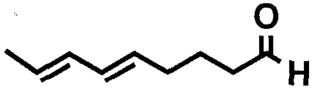
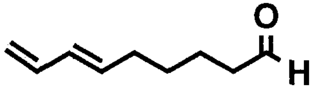
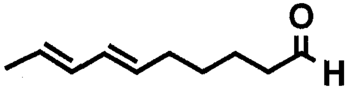
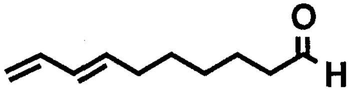
(1-3)

7 1 8 9

The results of these intramolecular Diels-Alder reaction are presented in Table 1-2. All reactions were carried out in THF under high-dilution conditions (0.03 M solution) for minimizing the intermolecular reaction. In entries 1-4, the adducts were obtained in modest yields as the result of internal cycloaddition of selenoaldehydes. In entry 5, however, the expected bicyclic adduct having the fused six- and seven-membered rings was hardly obtained because of the increased ring strain compared with those in bicyclo[4.4.0] and [4.3.0] systems.

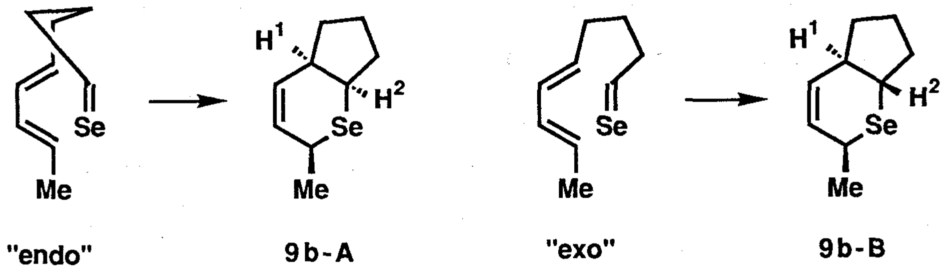
Stereo- and regio-chemistry of the intramolecular Diels-Alder reaction are an interesting problem.[22] All reactions gave only two stereoisomers A and B with respect to the bridgehead hydrogens (Scheme 1-2). For example, the reaction of 7b gave 9b-A and 9b-B in a ratio of 65 : 35. The cofiguration of the isomers was deduced from careful analysis of the 400 MHz NMR spectra. The J_{12} values in 9b-A (7.6 Hz) and 9b-B (11.6 Hz)

Table 1-2. Reaction of Dienals 7 with 1 in the Presence of 10 mol% of n-BuLi at 55°C in THF

entry	dienal		time (h)	bicyclic adduct 9		
				comp.	yield[a] (%)	A : B[b]
1		(7a)	6	9a	66	56 : 44
2		(7b)	6	9b	63	65 : 35
3		(7c)	6	9c	70	56 : 44
4		(7d)	6	9d	70	55 : 45
5		(7e)	10	9e	—[c]	—

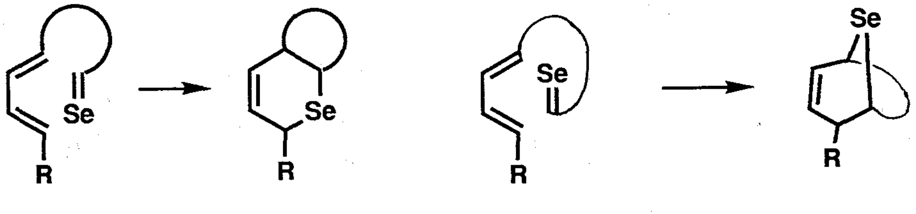
[a] Isolated yield. [b] The ratio was determined by ^{1}H-NMR.

[c] The complex mixture was obtained.



Scheme 1-2

are consistent with the cis-fused and the trans-fused ring structures, respectively. The stereochemistry of other bicyclic adducts was determined similarly. In all cases, the major products were derived from "endo" transition states, which coincided with the results seen in the intermolecular analogues.[1] On the other hand, the regiochemistry of the present intramolecular cycloaddition was completely controlled as type I shown in Scheme 1-3. Cycloadducts of the type II were not obtained. These characteristic features of the intramolecular cycloaddition of selenoaldehydes are very much similar to those of corresponding thioaldehydes reaction.[19,20]



type I

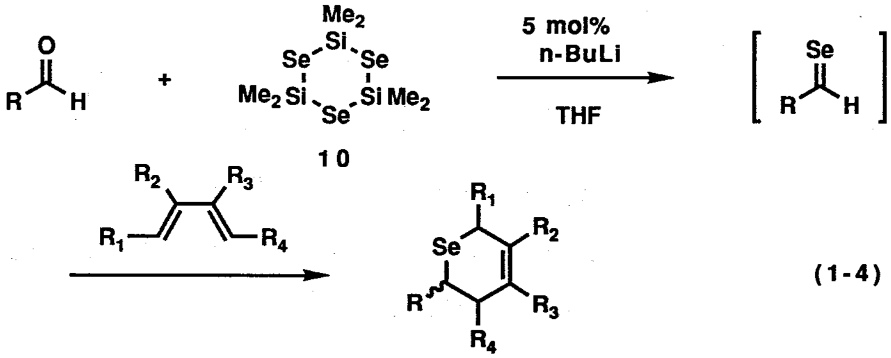
Scheme 1-3

type II

The present reaction not only represents the first example of intramolecular trapping of selenoaldehydes but also offers a new entry to selenium containing carbocycles.

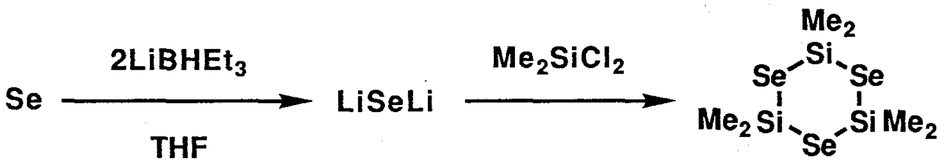
1-4 Generation and Trapping of Selenoaldehydes Using Hexamethylcyclotrisilaselenane

In section 1-2, a simple and convenient method for the direct conversion of aldehydes to selenoaldehydes by the use of bis(trimethylsilyl) selenide as a selenating reagent was described. However, the trapping of the selenoaldehydes generated in situ by this method was successful only in the Diels-Alder reaction with cyclopentadiene. Attempts to trap those by other acyclic 1,3-dienes resulted in the formation of a complex mixture. So, other selenating reagents were investigated in order to generate selenoaldehydes more efficiently. As a result, it turned out that the use of hexamethylcyclotrisilaselenane **10** as a selenating reagent leads effectively to the successful trapping of selenoaldehydes by an acyclic 1,3-diene (eq. 1-4). The presence of a catalytic amount of butyllithium was also essential for the generation of selenoaldehydes in this method using **10**.



(1-4)

10 was prepared in a similar manner as the synthesis of bis(trimethylsilyl) selenide 1, in which the reduction of a elemental selenium by lithium triethylborohydride (Super Hydride®) followed by the silylation with dichlorodimethylsilane were involved as shown in eq. 1-5. The structure of 10 was



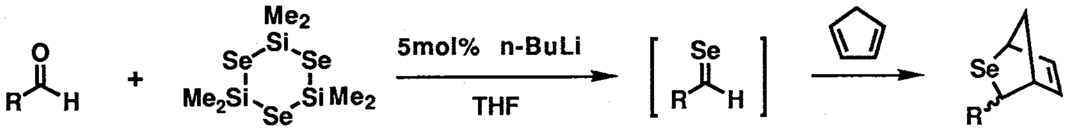
(1-5)

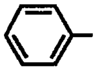
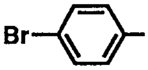
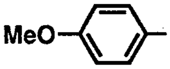
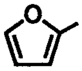
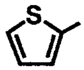
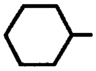
10 Y: 88%

confirmed by ^{1}H-, ^{13}C-, ^{77}Se-NMR, mass, and exact mass spectral data (see experimental section). Thermodynamically stable six-membered ring was preferentially formed under present conditions. As 10 was sensitive to moisture or oxygen, a one-pot operation was performed without the isolation of 10 for selenoaldehyde synthesis. The removal of triethylborane by-produced at the stage of reduction of selenium by Super Hydride® was essential for this one-pot procedure.

Generation of selenoaldehydes in the presence of cyclopentadiene or acyclic 1,3-dienes led to the formation of cycloadducts in good to excellent yields for all cases. These results are summarized in Tables 1-3 and 1-4, respectively. In the former an apparent preference for the formation of endo adducts was observed, similar to the results of selenoaldehyde

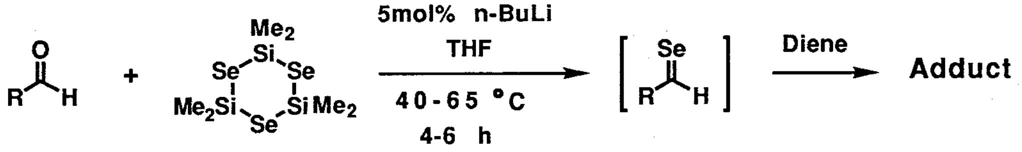
Table 1-3. Reaction of 10 with Aldehydes in the Presence of Cyclopentadiene

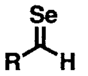
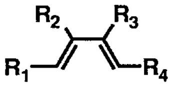
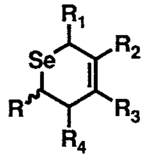
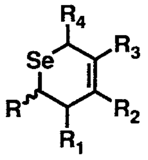
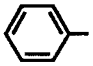
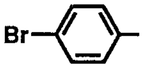
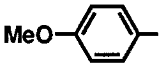
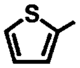


RCHO R	temp. (°C)	time (h)	yield[a] (%)	isomer ratio[b] endo:exo
	60	5	80	4 : 1
	40	4	87	3 : 1
	50	5	62	3 : 1
	40	4	76	2 : 1
	40	6	94	3 : 1
n-Pr	60	5	67	4 : 1
	60	4	89	10 : 1
i-Pr	60	4	69	10 : 1
t-Bu	60	5	80	>20 : 1

[a] Isolated yield. [b] Determined by ^{1}H-NMR.

Table 1-4. Reaction of 10 with Aldehydes in the Presence of an Acyclic 1,3-Diene

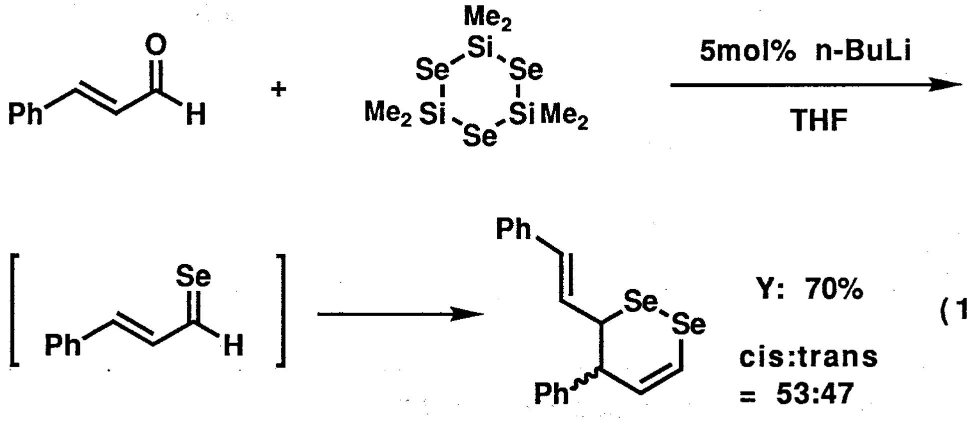


selenoaldehyde	diene				cycloadduct		
					yield(%)[a]	isomer ratio[b]	
							
R=	R1=	R2=	R3=	R4=			
	H	H	H	Me	62	62	38
	H	Me	H	Me	55	50	50
	H	Me	Me	H	61	———	
	H	Me	H	Me	80	67	33
	H	Me	H	Me	80	50	50
	H	Me	H	Me	94	62	38

[a]Isolated yield. [b]Determined by ^{1}H-NMR.

cycloaddition using 1. Regiochemistry in trapping of selenoaldehydes by an unsymmetrically substituted diene, for example 1,3-pentadiene, is an interesting problem.[23] The Diels-Alder reactions of aromatic selenoaldehydes, however, gave mixtures of inseparable regioisomers without a remarkable preference as shown in Table 1-4. Regioisomer ratios were determined by ^{1}H-NMR integration. The trapping of aliphatic selenoaldehydes by an acyclic diene was unsuccessful under these conditions.

On the other hand, the reaction of cinnamaldehyde with 10 in the absence of a diene under same condition yielded regioselectively the dimer of the corresponding selenocinnamaldehyde generated in situ in 70% yield as a mixture of cis and trans (53 : 47), as shown in eq. 1-6. The structure of this dimer was determined by decoupling experiments and careful analyses of coupling constants in ^{1}H-NMR spectrum.



(1-6)

1-5 Application to One-pot Synthesis of Unsymmetrical Selenium Compounds

In recent years, organoselenium reagents have emerged as potentially important synthetic intermediates.[24] Development of convenient and simple methods for the synthesis of these reagents is desirable. Symmetrical selenides are easily prepared by double alkylation of M_2Se where M is an alkali metal,[25] whereas unsymmetrical selenides are generally prepared by reduction of symmetrical diselenides to selenolates (RSe^-) and subsequent alkylation,[26] in which the starting diselenides must be independently prepared. Another route to unsymmetrical selenides is based on the reaction of RLi with elemental selenium followed by alkylation with an appropriate alkyl halide.[27] This method is useful only when RLi is easily available. On the other hand, during the course of the study on the generation of selenoaldehydes described in section 1-2, it has been found that lithium triethylsilyl selenide **11** is generated from the treatment of bis(trimethylsilyl) selenide **1** with 1.0 equiv. of n-BuLi (eq. 1-7). In this section, it is

$$\underset{\mathbf{1}}{\mathrm{Me_3SiSeSiMe_3}} + n\text{-}\mathrm{BuLi} \longrightarrow \underset{\mathbf{11}}{\mathrm{LiSeSiMe_3}} + n\text{-}\mathrm{BuSiMe_3} \qquad (1\text{-}7)$$

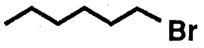
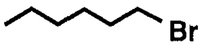
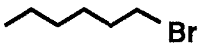
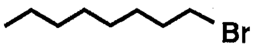
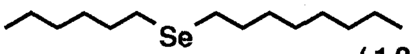
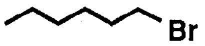
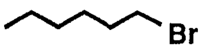
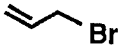
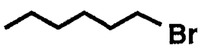
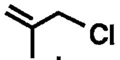
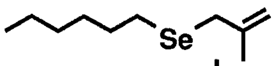
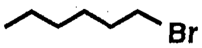
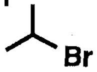
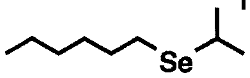
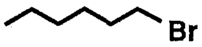
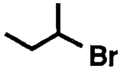
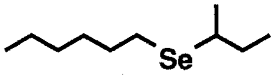
described that unsymmetrical selenium compounds (12) can be easily synthesized in a one-pot operation via the simple sequence shown in eq 1-8.

$$\underset{1}{Me_3SiSeSiMe_3} \xrightarrow[\substack{THF \\ 0\,^{\circ}C,\ 30\ min}]{n\text{-}BuLi} \underset{11}{LiSeSiMe_3} \xrightarrow[30\,^{\circ}C,\ 2\ h]{R^1X} R^1SeSiMe_3$$

$$\xrightarrow[0\,^{\circ}C,\ 30\ min]{n\text{-}BuLi} R^1SeLi \xrightarrow[30\,^{\circ}C,\ 2\ h]{R^2X} \underset{12}{R^1SeR^2} \quad \begin{array}{l} R^1,\ R^2 \\ =\text{alkyl,acyl,etc} \end{array} \qquad (1\text{-}8)$$

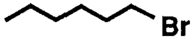
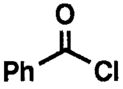
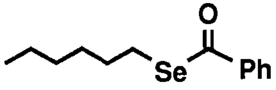
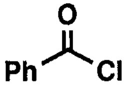
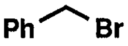
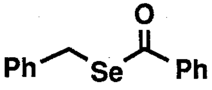
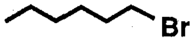
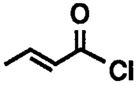
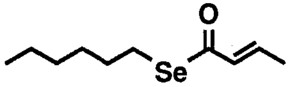
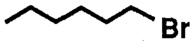
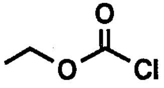
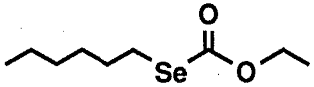
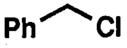
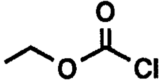
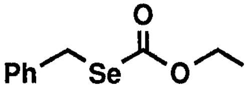
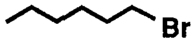
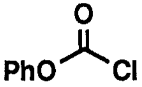
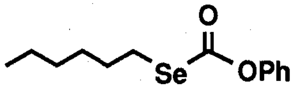
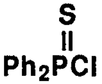
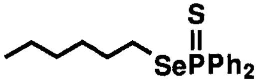
The results of synthesis of unsymmetrical selenides and other selenium compounds by this convenient method are listed in Tables 1-5 and 1-6, respectively. In most cases hexyl bromide was used as the first alkyl halide R^1X. The yield of simple alkyl selenides exceeded 90% (entries 1 and 2). Benzyl and allyl selenides were also prepared in satisfactory yields (entries 3-5). For the synthesis of secondary alkyl selenides, the addition of 1.0 equiv. of HMPA at the stage of the second alkylation resulted in better yields (entries 6 and 7). Furthermore, as shown in entries 8-14 (Table 1-6), the procedure can be applicable to a wide range of unsymmetrical selenium compounds. Thus, when acyl chloride, chloroformates, and phosphinothioyl chloride were used as the second halide R^2X, the corresponding selenolesters (12h-12j), selenolcarbo-

Table 1-5. Preparation of Unsymmetrical Selenides Using 1 and Alkyl Halides

entry	R^1X	R^2X	product	yield(%)[a]
1			 (12a)	91
2			 (12b)	97
3			 (12c)	88[b,c]
4			 (12d)	67
5			 (12e)	65
6			 (12f)	64[b,c]
7			 (12g)	70[b]

[a] Isolated yield. [b] NMR yield. [c] 1.0 equiv. of HMPA was added.

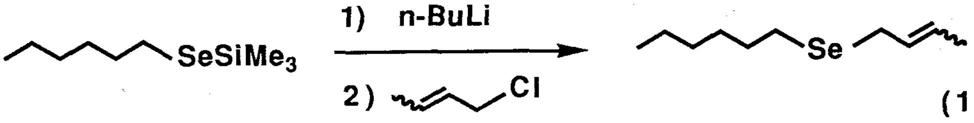
Table 1-6. Preparation of Selenium Compounds Using 1 and Various Halides

entry	R^1X	R^2X	product		yield(%)[a]
8				(12h)	79
9				(12i)	70[b]
10				(12j)	31
11				(12k)	75
12				(12l)	58[b]
13				(12m)	33
14		 $Ph_2P(=S)Cl$		(12n)	63

[a] Isolated yield. [b] NMR yield.

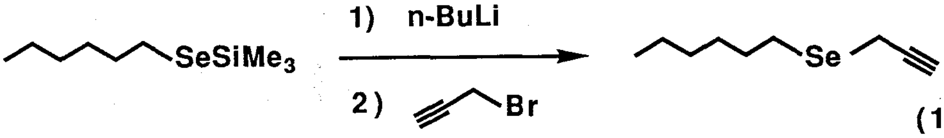
nates (**12k**-**12m**), and phosphinothioyl selenide (**12n**) were yielded, respectively.

The mode of substitution in this reaction was studied on allyllic or propargyllic system. In the second alkylation, crotyl chloride and propargyl bromide were displaced by a clean S_N2 process to give **12o** and **12p**, respectively, and no products arising from a competitive allyllic rearrangement could be detected (eqs. 1-9 and 1-10).



(1-9)

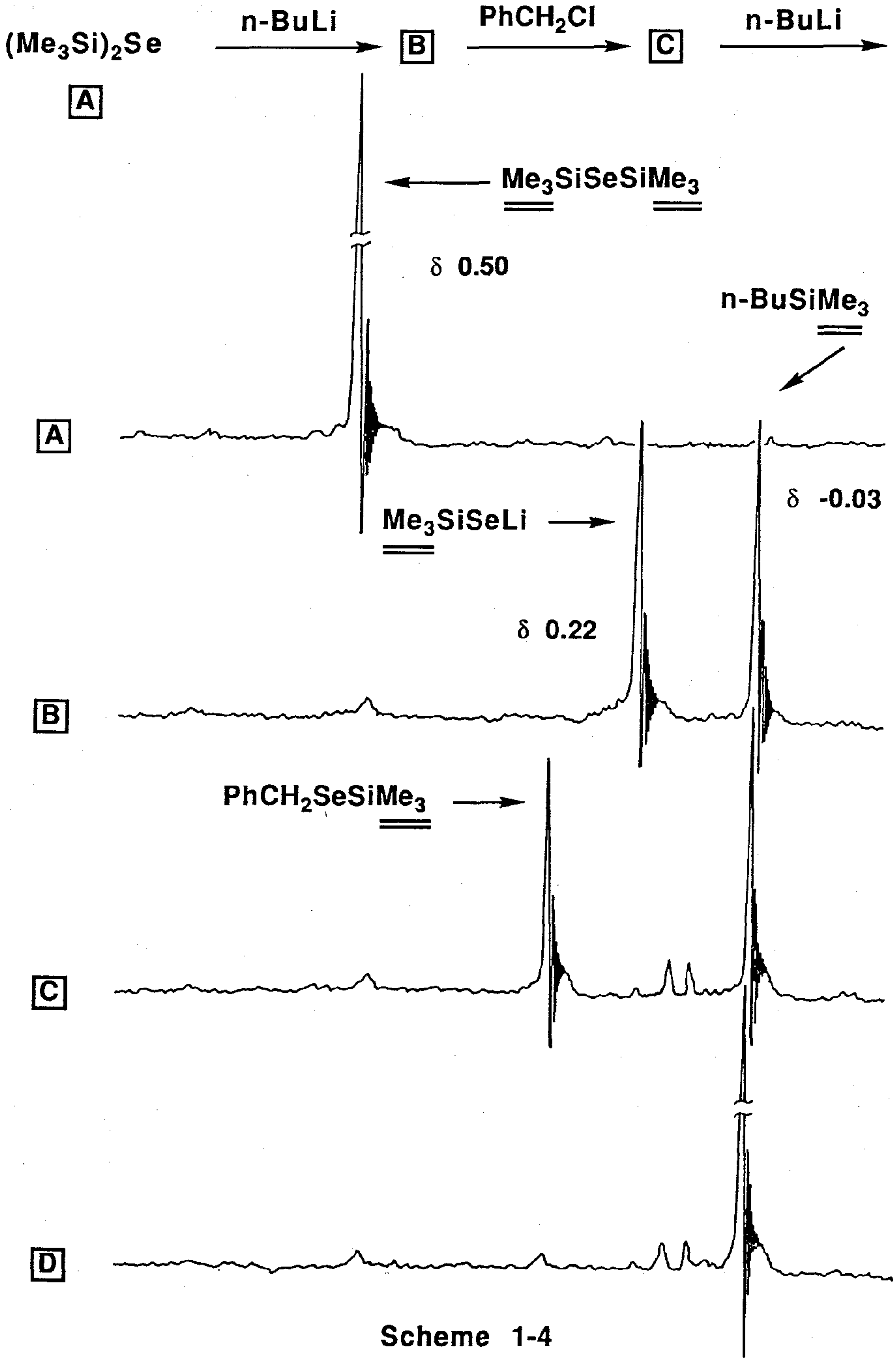
12o Y: 70%



(1-10)

12p Y: 50%

It seems that in the present reaction, both trimethylsilyl groups of **1** are displaced by butyl anion to give butyltrimethylsilane. To confirm this point, the reaction was followed by ^{1}H-NMR (Scheme 1-4). The signals corresponding to **11** and butyltrimethylsilane in eq. 1-7 appeared as singlets at δ 0.22 and -0.03, respectively, and these two peaks showed about the same hight. After the reaction with the second BuLi, the hight of the signal at δ -0.03 increased greatly and no other significant peak was observed in Me_3Si region. Interes-


(Me3Si)2Se
A
n-BuLi
B
PhCH2Cl
C
n-BuLi
D
Me3SiSeSiMe3
δ 0.50
n-BuSiMe3
δ -0.03
Me3SiSeLi
δ 0.22
PhCH2SeSiMe3
A
B
C
D

Scheme 1-4

tingly, even though **1** was treated with 2.0 equivalent of n-BuLi, the ^{1}H-NMR spectra of the reaction mixture were the same as those obtained from the reaction with 1.0 equivalent of n-BuLi. This result shows that the reaction of **1** with n-BuLi proceeds with a 1:1 stoichiometry and does not afford Li_2Se in situ.[28]

1-5 Experimental

Apparatus

Infrared spectra were obtained on a JASCO A-202 spectrometer and absorptions are reported in reciprocal centimeters. ^{1}H-NMR spectra were determined on a JEOL JNM-GX-400 spectrometer at 399.65 MHz and are reported in parts per million (δ) downfield from internal tetramethylsilane (TMS) in $CDCl_3$. Data are reported as follows: chemical shift, multiplicity (s= singlet, d=doublet, t=triplet, q=quartet, m=multiplet, br= broad), coupling constant(Hz), integration, and interpretation. ^{13}C-NMR spectra were recorded on a JEOL JNM-GX-400 spectrometer at 100.40 MHz and are reported in ppm from TMS. ^{77}Se-NMR spectrum was recorded on a JEOL JNM-GSX-270 spectrometer at 51.07 MHz and is reported in ppm from external dimethyl selenide (Me_2Se, neat). Mass spectra were recorded on a Hitachi M-80 or a JEOL JMS-DX303 spectrometer. Elemental analyses were performed on a Yanagimoto CHN-Corder MT-2.

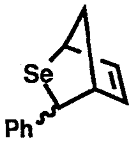
Materials

Tetrahydrofuran (THF) was freshly distilled from potassium /benzophenone just prior to use. Super Hydride®, butyllithium, and chloroform-d were purchased from Aldrich Chemicals, Ltd.

and used without purification. Metallic selenium (99.999%) was purchased from Nakarai Chemicals, Ltd. Chlorotrimethylsilane and dichlorodimethylsilane were distilled from calcium hydride. Cyclopentadiene was obtained by heating (160-180°C) technical dicyclopentadiene carefully under a fractionating column. The other dienes and aldehydes were purchased from commercial sources and purified by distillation. Bis(trimethylsilyl) selenide[10] and dienals[21] were prepared according to the reported procedures.

<u>General Procedure for the Generation and Trapping of Selenoaldehydes Using Bis(trimethylsilyl) Selenide</u>

3-Phenyl-2-selenabicyclo[2.2.1]hept-5-ene (endo:exo=4:1)



Butyllithium (1.6 M solution in hexane, 0.063 mL, 0.1 mmol) was added to a solution of bis(trimethylsilyl) selenide (225 mg, 1.0 mmol) in THF (30 mL) at 0 °C, cyclopentadiene (198 mg, 3.0 mmol) and benzaldehyde (159 mg, 1.5 mmol) were added in that order. The reaction mixture was stirred at 25 °C for 7 h. Evaporation of the solvent followed by a flash chromatography on silica gel (hexane-dichloromethane, 2:1) yielded the selenobenzaldehyde cycloadduct (172 mg, 73% yield) as a 4:1 mixture of endo and exo isomers.

Bp 95-105°C (bath temp., 0.1 mmHg)(bulb-to-bulb distillation).

TLC (SiO_2, Merck #5725) R_f: 0.49 (hexane-dichloromethane, 2:1).

^{1}H-NMR <u>endo</u> δ 7.16-7.39(m, 5H, ArH), 6.55(dd, J_1=2.8Hz, J_2=5.5 Hz, 1H, C-6), 5.50(dd, J_1=3.1Hz, J_2=5.5Hz, 1H, C-5), 5.23(d, J=4.0Hz, 1H, C-3), 4.43(br s, 1H, C-1), 3.32(br s, 1H, C-4), 1.82-1.88(m, 2H, C-7).

<u>exo</u> δ 7.17-7.60(m, 5H, ArH), 6.44(dd, J_1=3.1Hz, J_2=5.5 Hz, 1H, C-6), 5.94(dd, J_1=3.1Hz, J_2=5.5Hz, 1H, C-5), 4.53(br s, 1H, C-1), 4.32(s, 1H, C-3), 3.10(br s, 1H, C-4), 2.12(d, J=9.8Hz, 1H, C-7), 1.82-1.88(m, 1H, C-7).

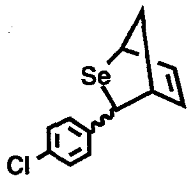
IR (NaCl, neat) 3054, 2950, 1600, 1498, 1450, 1345, 1071, 731, 699 cm^{-1}.

MS m/s(relative intensity) 236(M^+, 24), 170(100), 155(28), 91(14), 28(40).

Anal. Calcd for $C_{12}H_{12}Se$: C, 61.28; H, 5.14. Found: C, 61.22; H, 5.20.

Reactions under the same conditions and similar workup as described above gave the other selenoaldehyde cycloadducts with cyclopentadiene.

3-(4-Chlorophenyl)-2-selenabicyclo[2.2.1]hept-5-ene (endo:exo= 4:1)



Bp 120-130°C (bath temp., 0.1 mmHg)(bulb-to-bulb distillation).

TLC (SiO_2, Merck #5715) R_f: 0.53 (hexane-dichloromethane, 2:1).

^{1}H-NMR <u>endo</u> δ 7.10-7.42(m, 4H, ArH), 6.56(dd, J_1=3.1Hz, J_2=5.5 Hz, 1H, C-6), 5.47(dd, J_1=3.1Hz, J_2=5.5Hz, 1H, C-5), 5.17(d, J=4.0Hz, 1H, C-3), 4.44(br s, 1H, C-1), 3.28(br s, 1H, C-4), 1.82-1.86(m, 2H, C-7).

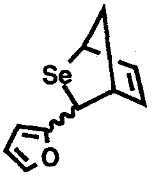
<u>exo</u> δ 7.10-7.42(m, 4H, ArH), 6.44(dd, J_1=2.8Hz, J_2=5.5Hz 1H, C-6), 5.94(dd, J_1=3.1Hz, J_2=5.5Hz, 1H, C-5), 4.55(br s, 1H, C-1), 4.26(s, 1H, C-3), 3.05(br s, 1H, C-4), 2.06 (d, J=10.1Hz, 1H, C-7), 1.82-1.86(m, 1H, C-7).

IR (NaCl, neat) 3056, 2942, 1491, 1444, 1407, 1348, 1085, 1014, 765, 739 cm^{-1}.

MS, m/e(relative intensity) 270(M^+, 18), 204(100), 153(16), 125 (13), 66(20).

Anal. Calcd for $C_{12}H_{11}ClSe$: C, 53.46; H, 4.11. Found: C, 53.31; H, 4.48.

3-(2-Furyl)-2-selenabicyclo[2.2.1]hept-5-ene (endo:exo=2:1)



Bp 75-85°C (bath temp., 0.1 mmHg)(bulb-to-bulb distillation).

TLC (SiO_2, Merck #5715) R_f: 0.43 (hexane-dichloromethane, 2:1).

^{1}H-NMR <u>endo</u> δ 7.31(dd, J_1=0.9Hz, J_2=1.8Hz, 1H, FurylH), 6.54 (dd, J_1=3.1Hz, J_2=5.5Hz, 1H, C-6), 6.22(dd, J_1=1.8Hz, J_2=3.1Hz, 1H, FurylH), 6.04(d, J=3.1Hz, 1H, FurylH), 5.67(dd, J_1=3.1Hz, J_2=5.5Hz, 1H, C-5), 5.22(d, J=4.0Hz, 1H, C-3), 4.43(br s, 1H, C-1), 3.47(br s, 1H, C-4), 1.86 (dt, J_1=2.4Hz, J_2=9.5Hz, 1H, C-7), 1.78(d, J=9.5Hz, 1H, C-7).

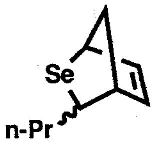
<u>exo</u> δ 7.37(dd, J_1=0.9Hz, J_2=1.8Hz, 1H, FurylH), 6.45(dd J_1=3.1Hz, J_2=5.5Hz, 1H, C-6), 6.31(dd, J_1=1.8Hz, J_2=3.1 Hz, 1H, FurylH), 6.23(d, J=3.1Hz, 1H, FurylH), 5.87(dd, J_1=3.1Hz, J_2=5.5Hz, 1H, C-5), 4.52(br s, 1H, C-1), 4.25 (s, 1H, C-3), 3.24(br s, 1H, C-4), 2.12(d, J=10.1Hz, 1H, C-7), 1.87-1.90(m, 1H, C-7).

IR (NaCl, neat) 2952, 2923, 1509, 1440, 1344, 1011, 727 cm^{-1}.

MS, m/e(relative intensity) 226(M^+, 24), 160(100), 156(47), 115 (17), 91(11), 66(25), 28(51).

Anal. Calcd for $C_{10}H_{10}OSe$: C, 53.35; H, 4.48. Found: C, 53.48; H, 4.63.

3-Propyl-2-selenabicyclo[2.2.1]hept-5-ene (endo:exo=7:1).



Bp 35-40°C (bath temp., 0.1 mmHg)(bulb-to-bulb distillation).

TLC (SiO_2, Merck #5715) R_f: 0.53 (hexane-dichloromethane, 2:1).

^{1}H-NMR <u>endo</u> δ 6.43(dd, J_1=2.8Hz, J_2=5.5Hz, 1H, C-6), 5.65(dd, J_1=3.1Hz, J_2=5.5Hz, 1H, C-5), 4.25(br s, 1H, C-1), 4.16 (ddd, J_1=3.7Hz, J_2=5.5Hz, J_3=9.7Hz, 1H, C-3), 3.15(br s, 1H, C-4), 1.75(dt, J_1=2.7Hz, J_2=9.5Hz, 1H, C-7), 1.63(d, J=9.5Hz, 1H, C-7), 1.36-1.43(m, 2H, C-8), 1.25-1.32(m, 2H, C-9), 0.91(t, J=7.3Hz, 3H, C-10).

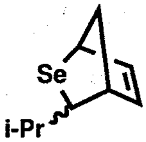
<u>exo</u> δ 6.32(dd, J_1=2.8Hz, J_2=5.5Hz, 1H, C-6), 5.76(dd, J_1=3.3Hz, J_2=5.5Hz, 1H, C-5), 4.30(br s, 1H, C-1), 3.16 (br, 1H, C-3), 2.86(br s, 1H, C-4), 1.81-1.88(m, 2H, C-8), 1.78-1.80(m, 1H, C-7), 1.65-1.69(m, 1H, C-7), 1.45 -1.55(m, 2H, C-9), 0.96(t, J=7.3Hz, 3H, C-10).

IR (NaCl, neat) 2948, 2925, 1462, 1261, 1108, 778, 734 cm^{-1}.

MS, m/e(relative intensity) 202(M^+, 46), 136(33), 134(19), 121 (19), 79(71), 66(50), 55(100), 32(43), 28(100).

Anal. Calcd for $C_9H_{14}Se$: C, 53.74; H, 7.01. Found: C, 53.75; H, 7.17.

3-Isopropyl-2-selenabicyclo[2.2.1]hept-5-ene (endo:exo=10:1)



Bp 30-35°C (bath temp., 0.1 mmHg)(bulb-to-bulb distillation).

TLC (SiO_2, Merck #5715) R_f: 0.54 (hexane-dichloromethane, 2:1).

^{1}H-NMR <u>endo</u> δ 6.44(dd, J_1=2.8Hz, J_2=5.5Hz, 1H, C-6), 5.66(dd,

J_1=3.1Hz, J_2=5.5Hz, 1H, C-5), 4.23(br s, 1H, C-1), 3.85 (dd, J_1=3.7Hz, J_2=11.0Hz, 1H, C-3), 3.24(br s, 1H, C-4), 1.75(dt, J_1=2.7Hz, J_2=9.5Hz, 1H, C-7), 1.64(d, J=9.5Hz, 1H, C-7), 1.29(dq, J_1=6.7Hz, J_2=11.0Hz, 1H, C-8), 1.12 (d, J=6.7Hz, 3H, C-9), 0.95(d, J=6.7Hz, 3H, C-9).

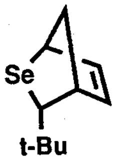
<u>exo</u> δ 6.33(dd, J_1=2.8Hz, J_2=5.5Hz, 1H, C-6), 5.78(dd, J_1=3.4Hz, J_2=5.5Hz, 1H, C-5), 4.27(br s, 1H, C-1), 3.01 (br s, 1H, C-4), 2.94(d, J=9.8Hz, 1H, C-3), 1.63-1.80(m, 2H, C-7), 1.32-1.42(m, 1H, C-8), 1.14(d, J=6.7Hz, 3H, C-9), 1.11(d, J=6.7Hz, 3H, C-9).

IR (NaCl, neat) 2951, 2923, 1464, 1362, 1238, 1119, 916, 865, 768, 730 cm^{-1}.

MS, m/e(relative intensity) 202(M^+, 64), 136(62), 134(31), 121 (43), 79(41), 66(51), 55(100).

Anal. Calcd for $C_9H_{14}Se$: C, 53.74; H, 7.01. Found: C, 53.81; H, 7.22.

<u>endo</u>-3-tert-Butyl-2-selenabicyclo[2.2.1]hept-5-ene



Bp 35-40°C (bath temp., 0.1 mmHg)(bulb-to-bulb distillation).

TLC (SiO_2, Merck #5715) R_f: 0.58 (hexane-dichloromethane, 2:1).

^{1}H-NMR δ 6.34(dd, J_1=3.1Hz, J_2=5.5Hz, 1H, C-6), 5.69(dd, J_1=3.1 Hz, J_2=5.5Hz, 1H, C-5), 4.17(d, J=3.4Hz, 1H, C-3), 4.16

(br s, 1H, C-1), 3.22(br s, 1H, C-4), 1.63-1.70(m, 2H, C-7), 0.96(s, 9H, C-9).

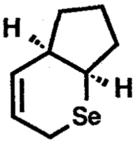
IR (NaCl, neat) 2953, 1476, 1468, 1391, 1362, 1263, 1258, 1075, 860, 758, 727 cm^{-1}.

MS, m/e(relative intensity) 216(M$^+$, 21), 150(26), 148(18), 69 (100), 66(23), 32(100), 28(100).

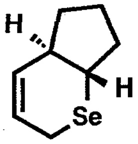
Anal.Calcd for $C_{10}H_{16}Se$: C, 55.81; H, 7.49. Found: C, 55.91; H, 7.68.

General Procedure for the Intramolecular Diels-Alder Reaction of Selenoaldehydes

2-Selenabicyclo[4.3.0]non-4-ene 9a (cis:trans=56:44)



cis



trans

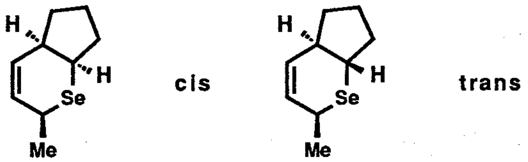
Butyllithium (1.6 M solution in hexane, 0.050 mL, 0.08 mmol) was added to a solution of bis(trimethylsilyl) selenide (180 mg, 0.8 mmol) in THF (30 mL) at 0°C under nitrogen. After stirring for 30 min at 0°C, 5,7-octadienal 7a (105 mg, 0.85 mmol) was added. The reaction mixture was stirred at 55°C for 6 h. Evaporation of the solvent followed by a flash chromatography on silica gel (hexane) yielded 2-selenabicyclo[4.3.0]-non-4-ene 9a (99 mg, 66% yield) in a cis/trans ratio 5 of 56 : 44.

^{1}H-NMR *cis* δ 1.15-1.28(m, 1H), 1.48-2.27(m, 5H), 2.36(br s, 1H) 2.91(dd, J_1=4.3Hz, J_2=16.2Hz, 1H), 3.16-3.22(m, 1H), 3.35-3.42(m, 1H), 5.76-5.83(m, 2H).

trans δ 1.51-2.20(m, 7H), 2.66(dt, J_1=7.0Hz, J_2=11.9Hz, 1H), 3.11-3.18(m, 1H), 3.35-3.42(m, 1H), 5.74-5.92(m, 2H).

MS, m/e(relative intensity) 188(M^+, 25), 107(50), 91(20), 79(100), 67(17), 41(25), 28(19).

3-Methyl-2-selenabicyclo[4.3.0]non-4-ene **9b** (cis:trans=65:35)

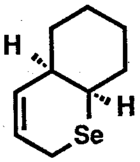


^{1}H-NMR *cis* δ 1.40(d, J=7.3Hz, 3H), 1.52-2.24(m, 7H), 3.64(ddd, J_1=2.7Hz, J_2=5.2Hz, J_3=7.6Hz, 1H), 3.65-3.73(m, 1H), 5.62(dt, J_1=2.4Hz, J_2=10.7Hz, 1H), 5.77(ddd, J_1=2.7Hz, J_2=4.6Hz, J_3=10.7Hz, 1H).

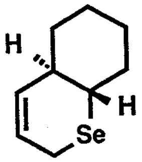
trans δ 1.55(d, J=7.3Hz, 3H), 1.23-2.20(m, 7H), 2.71(dt, J_1=6.7Hz, J_2=11.6Hz, 1H), 3.66-3.73(m, 1H), 5.65(ddd, J_1=2.7Hz, J_2=4.3Hz, J_3=10.7Hz, 1H), 5.90(dt, J_1=2.8Hz, J_2=10.7Hz, 1H).

MS, m/e(relative intensity) 202(M^+, 30), 135(21), 121(60), 105 (18), 93(55), 79(100), 67(22), 55(43), 41(26).

2-Selenabicyclo[4.4.0]oct-4-ene **9c** (cis:trans=56:44)



cis

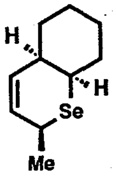


trans

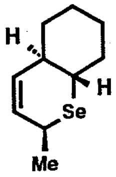
^{1}H-NMR cis δ 1.31-1.95(m, 8H), 2.39(br s, 1H), 3.10(br d, J=16.2z, 1H), 3.21-3.33(m, 2H), 5.62(ddt, J_1=2.1Hz, J_2=4.3Hz, J_3=10.7Hz, 1H), 5.76-5.81(m, 1H).

trans δ 1.05-1.18(m, 1H), 1.35-2.06(m, 7H), 2.18-2.27(m, 1H), 2.80(ddd, J_1=3.4Hz, J_2=10.1Hz, J_3=11.9Hz, 1H), 3.01 (ddt, J_1=2.1Hz, J_2= 5.5Hz, J_3=16.2Hz, 1H), 3.51(ddt, J_1=2.7Hz, J_2=3.4Hz, J_3=16.2Hz, 1H), 5.49(dd, J_1=1.8Hz, J_2=10.7Hz, 1H), 5.73(ddt, J_1=2.7Hz, J_2=5.4Hz, J_3=10.7Hz,1H)

3-Methyl-2-selenabicyclo[4.4.0]oct-4-ene **9d** (cis:trans=55:45)



cis



trans

^{1}H-NMR cis δ 1.43(d, 3H, J=7.0Hz), 1.36-2.18(m, 9H), 3.58(dd, J_1=4.3Hz, J_2=8.2Hz, 1H), 3.75-3.81(m, 1H), 5.55-5.64(m, 2H).

trans δ 1.57(d, 3H, J=7.0Hz), 1.09-1.20(m, 1H), 1.35-2.16(m, 8H), 2.77(ddd, J_1=3.4Hz, J_2=10.4Hz, J_3=11.9Hz, 1H), 3.46-3.52(m, 1H), 5.46(dt, J_1=1.8Hz, J_2=10.7Hz), 5.58-5.64(m, 1H).

Preparation of Hexamethylcyclotrisilaselenane 10

A 100-mL three-necked, round-bottomed flask was flamed and cooled under an argon atmosphere. The flask was charged with lithium triethylborohydride (Super Hydride®)(1.0 M solution in THF, 44 mL, 44 mmol). The flask was cooled in an ice bath, and selenium shot (Nakarai Chemicals, Ltd., 99.999%, 1.58 g, 20 mmol) was added in portions. The reaction mixture was warmed to room temperature and stirred for 2 h. The reaction mixture was cooled to ice-bath temperature, and dichlorodimethylsilane (3.10 g, 24 mmol) was added in one portion. The resulting mixture was stirred for 2 h at room temperature. The low-boiling volatiles were removed by a careful reduced distillation directly from the reaction vessel. The product was subsequently distilled at higher vacuum, again directly from the reaction vessel, to give 2.41 g (88% yield) of 10 as a colorless oil, bp 100-105 °C (0.15 mmHg). The pot residue was treated with methanol under an inert atmosphere before disposal.

^{1}H-NMR δ 0.90 (s, $-CH_3$).

^{13}C-NMR δ 8.66 ($-CH_3$).

^{77}Se-NMR δ -248.40.

MS, m/e 414, 412, 397, 261.

Exact MS, Calcd for $C_6H_{18}Se_3Si_3(Se^{80})$: 413.8211.

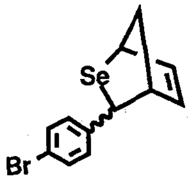
Found: 413.8203.

One-pot Procedure for Selenoaldehyde Cycloaddition Using 10

Selenium shot (79 mg, 1.0 mmol) was added to 1 M lithium triethylborohydride in THF (2.2 mL, 2.2 mmol) at 0 °C under argon. After the formation of dilithioselenide (about 30 min), dichlorodimethylsilane (168 mg, 1.3 mmol) was added in one portion. The reaction mixture was stirred for 2 h at room temperature. After the removal of the low-boiling volatiles, THF (30 mL) as a solvent was added and then butyllithium (1.6 M solution in hexane, 0.031 mL, 0.05 mmol) was added at 0 °C. After stirring for 30 min at 0 °C, excess amounts of diene and aldehyde (1.5 mmol) were added in that order. The reaction mixture was stirred at the prescribed temperature. Evaporation of the solvent followed by a flash column chromatography on silica gel (hexane-dichloromethane, 2:1) yielded the Diels-Alder adduct of selenoaldehyde with the diene.

Characteristic ^{1}H-NMR data of cycloadducts except for those described at section 1-2 are as follows.

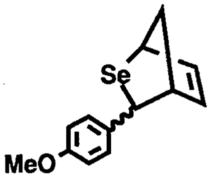
3-(4-Bromophenyl)-2-selenabicyclo[2.2.1]hept-5-ene
(endo:exo=3:1)



^{1}H-NMR <u>endo</u> δ 7.06-7.37(m, 4H, ArH), 6.56(dd, J_1=3.1Hz, J_2=5.4 Hz, 1H, C-6), 5.47(dd, J_1=3.1Hz, J_2=5.4Hz, 1H, C-5), 5.16(d, J=3.9Hz, 1H, C-3), 4.46(br s, 1H, C-1), 3.29(br s, 1H, C-4), 1.82-2.01(m, 2H, C-7).

<u>exo</u> δ 7.10-7.41(m, 4H, ArH), 6.44(dd, J_1=2.9Hz, J_2=5.4 Hz, 1H, C-6), 5.94(dd, J_1=2.9Hz, J_2=5.4Hz, 1H, C-5), 4.55(br s, 1H, C-1), 4.24(s, 1H, C-3), 3.05(br s, 1H, C-4), 1.82-2.06(m, 2H, C-7).

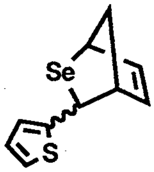
3-(4-Methoxyphenyl)-2-selenabicyclo[2.2.1]hept-5-ene (endo:exo=3:1)



^{1}H-NMR <u>endo</u> δ 6.62-7.18(m, 4H, ArH), 6.47(dd, J_1=2.9Hz, J_2=5.6 Hz, 1H, C-6), 5.46(dd, J_1=2.9Hz, J_2=5.6Hz, 1H, C-5), 5.11(d, J=3.9Hz, 1H, C-3), 4.37(br s, 1H, C-1), 3.20(br s, 1H, C-4), 1.72-1.78(m, 2H, C-7).

<u>exo</u> δ 6.70-7.40(m, 4H, ArH), 6.39(dd, J_1=2.9Hz, J_2=5.5 Hz, 1H, C-6), 5.88(dd, J_1=2.9Hz, J_2=5.5Hz, 1H, C-5), 4.42(br s, 1H, C-1), 4.21(s, 1H, C-3), 2.96(br s, 1H, C-4), 1.72-2.10(m, 2H, C-7).

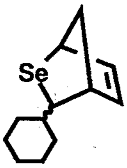
3-Thienyl-2-selenabicyclo[2.2.1]hept-5-ene (endo:exo=2:1)



^{1}H-NMR endo δ 6.84-7.26(m, 3H, thienyl proton), 6.63(dd, J_1=2.9 Hz, J_2=5.5Hz, 1H, C-6), 5.67(dd, J_1=2.9Hz, J_2=5.5Hz, 1H, C-5), 5.50(d, J=3.9Hz, 1H, C-3), 4.45(br s, 1H, C-1), 3.37(br s, 1H, C-4), 1.85-1.92(m, 2H, C-7).

exo δ 6.84-7.26(m, 3H, thienyl proton), 6.45(dd, J_1=2.9 Hz, J_2=5.5Hz, 1H, C-6), 5.92(dd, J_1=2.9Hz, J_2=5.5Hz, 1H, C-5), 4.53(br s, 1H, C-1), 4.52(s, 1H, C-3), 3.14(br s, 1H, C-4), 1.86-2.24(m, 2H, C-7).

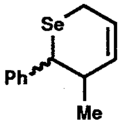
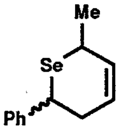
3-Cyclohexyl-2-selenabicyclo[2.2.1]hept-5-ene (endo:exo=10:1)



^{1}H-NMR endo δ 6.42(dd, J_1=2.7Hz, J_2=5.4Hz, 1H, C-6), 5.64(dd, J_1=2.7Hz, J_2=5.4Hz, 1H, C-5), 4.23(br s, 1H, C-1), 3.28 (br s, 1H, C-4), 0.80-1.80(m, 13H).

exo δ 6.38(dd, J_1=2.7Hz, J_2=5.4Hz, 1H, C-6), 5.77(dd, J_1 =2.7Hz, J_2=5.4Hz, 1H, C-5), 4.40(br s, 1H, C-1), 3.06(br s, 1H, C-4), 2.95(d, J=9.7Hz, 1H, C-3), 0.80-2.14(m, 13H).

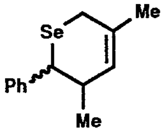
3,6-Dihydro-3-methyl-2-phenyl-2H-selenopyran (A) and 3,6-Dihydro-6-methyl-2-phenyl-2H-selenopyran (B) (A:B=62:38)


A

B

^{1}H-NMR A (mixture of cis and trans) δ 1.79(br s, 3H, Me), 0.97 (d, J=7.1Hz, 3H, Me), 0.95(d, J=7.1Hz, 3H, Me).

B (mixture of cis and trans) δ 1.85(br s, 3H, Me), 1.45 (d, J=7.3Hz, 3H, Me).

3,6-Dihydro-3,5-dimethyl-2-phenyl-2H-selenopyran (A) and 3,6-Dihydro-4,6-dimethyl-2-phenyl-2H-selenopyran (B) (A:B=50:50)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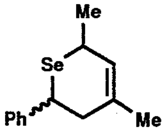
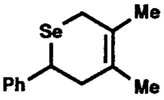

B

^{1}H-NMR A (mixture of cis and trans) δ 7.10-7.50(m, 5H, ArH), 5.40-5.60(m, 1H, olefinic proton), 1.86(br s, 3H, Me), 0.94(d, J=7.1Hz, 3H, Me), 0.92(d, J=7.1Hz, 3H, Me).

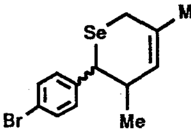
B (mixture of cis and trans) δ 7.10-7.50(m, 5H, ArH), 5.40-5.60(m, 1H, olefinic proton), 1.78(br s, 3H, Me), 1.58(d, J=7.3Hz, 3H, Me), 1.43(d, J=7.3Hz, 3H, Me).

3,6-Dihydro-4,5-dimethyl-2-phenyl-2H-selenopyran

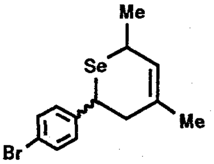


^{1}H-NMR δ 7.10-7.40(m, 5H, ArH), 4.19(dd, J_1=4.9Hz, J_2=9.8Hz, 1H), 3.44(d, J=14.4Hz, 1H), 3.08(d, J=14.4Hz, 1H), 2.24-2.81(m, 2H, methylene), 1.83(br s, 3H, Me), 1.75(br s, 3H, Me).

3,6-Dihydro-2-(4-bromophenyl)-3,5-dimethyl-2H-selenopyran (A) and 3,6-Dihydro-2-(4-bromophenyl)-4,6-dimethyl-2H-selenopyran (B) (A:B=67:33)



A

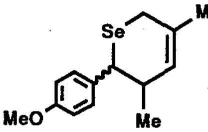


B

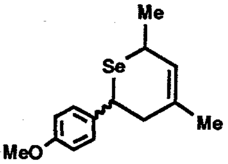
^{1}H-NMR A (mixture of cis and trans) δ 6.95-7.50(m, 4H, ArH), 5.30-5.50(m, 1H, olefinic proton), 1.79(br s, 3H, Me), 0.85(d, J=6.8Hz, 3H, Me).

B (mixture of cis and trans) δ 6.95-7.50(m, 4H, ArH), 5.30-5.50(m, 1H, olefinic proton), 1.70(br s, 3H, Me), 1.49(d, J=7.1Hz, 3H, Me), 1.35(d, J=7.1Hz, 3H, Me).

3,6-Dihydro-3,5-dimethyl-2-(4-methoxyphenyl)-2H-selenopyran (A) and 3,6-Dihydro-4,6-dimethyl-2-(4-methoxyphenyl)-2H-selenopyran (B) (A:B=50:50)



A



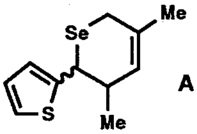
B

^{1}H-NMR A (mixture of cis and trans) δ 6.72-7.38(m, 4H, ArH), 5.40-5.60(m, 1H, olefinic proton), 3.78(s, 3H, Me), 1.86

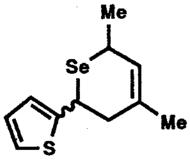
(br s, 3H, Me), 0.94(d, J=7.1Hz, 3H, Me), 0.91(d, J=7.1 Hz, 3H, Me).

B (mixture of cis and trans) δ 6.72-7.38(m, 4H, ArH), 5.40-5.60(m, 1H, olefinic proton), 3.77(s, 3H, Me), 1.77 (br s, 3H, Me), 1.58(d, J=7.1Hz, 3H, Me), 1.43(d, J=7.1 Hz, 3H, Me).

3,6-Dihydro-3,5-dimethyl-2-thienyl-2H-selenopyran (A) and 3,6-Dihydro-4,6-dimethyl-2-thienyl-2H-selenopyran (B) (A:B=62:38)



A

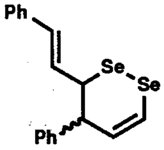


B

^{1}H-NMR A (mixture of cis and trans) δ 6.85-7.20(m, 3H, thienyl proton), 5.30-5.45(m, 1H, olefinic proton), 1.05(d, J=7.1Hz, 3H, Me), 1.01(d, J=7.1Hz, 3H, Me).

B (mixture of cis and trans) δ 6.85-7.20(m, 3H, thienyl proton), 5.30-5.45(m, 1H, olefinic proton), 1.88(br s, 3H, Me), 1.56(d, J=7.1Hz, 3H, Me), 1.43(d, J=7.1Hz, 3H, Me).

Dimer of selenocinnamaldehyde (cis:trans=53:47)



^{1}H-NMR δ 7.15-7.40(m, 10H, ArH), 5.90-6.97(m, olefinic proton), 4.91-5.11(m), 4.65(dd, J_1=7.3Hz, J_2=8.8Hz), 4.01-4.34(m)

One-pot Procedure for Synthesis of Unsymmetrical Selenium Compounds

A typical experimental procedure is exemplified by the synthesis of hexyl octyl selenide (**12b**). Butyllithium (1.6 M solution in hexane, 0.53 mL, 0.85 mmol) was added to a solution of bis(trimethylsilyl) selenide (80 mg, 0.80 mmol) in THF (20 mL) at 0 °C under nitrogen. After stirring for 30 min at 0 °C, hexyl bromide (140 mg, 0.85 mmol) in THF (5 mL) was added dropwise, and the mixture was stirred for 2 h at 30 °C. After cooling, the second butyllithium (0.85 mmol) and octyl bromide (164 mg, 0.85 mmol) were added in a similar manner as above. Extractive workup followed by a flash column chromatography on silica gel (hexane as eluent) yielded hexyl octyl selenide (**12b**)(215 mg, 0.78 mmol) in 97% yield.

^{1}H-NMR δ 2.55(t, J=7.3Hz, 4H), 1.07-1.90(m, 20H), 0.89(br t, J= 6.7Hz, 6H).

^{1}H-NMR data of other selenium compounds are as follows.

Dihexyl selenide (**12a**)

^{1}H-NMR δ 2.55(t, J=7.3Hz, 4H), 1.05-1.88(m, 16H), 0.88(br t, J= 6.7Hz, 6H).

Benzyl hexyl selenide (**12c**)

^{1}H-NMR δ 7.26-7.41(m, 5H, ArH), 3.78(s, 2H), 2.49(t, J=7.6Hz, 2H), 1.06-1.86(m, 8H), 0.88(br t, J=6.4Hz, 3H).

Allyl hexyl selenide (**12d**)

^{1}H-NMR δ 5.89(ddt, J_1=9.5Hz, J_2=17.1Hz, J_3=7.6Hz, 1H), 5.00(br d, J=17.1Hz, 1H, olefinic trans proton), 4.97(br d, J=9.5Hz, 1H, olefinic cis proton), 3.16(dd, J_1=7.6Hz, J_2=1.0Hz, 2H), 2.51(t, J=7.3Hz, 2H), 1.06-1.86(m, 8H), 0.89 (br t, J=6.1Hz, 3H).

Hexyl methallyl selenide (**12e**)

^{1}H-NMR δ 4.78(br d, J=1.0Hz, 2H), 3.15(s, 2H), 2.48(t, J=6.6Hz, 2H), 1.85(t, J=1.1Hz, 3H), 1.03-1.80(m, 8H), 0.89(br t, J=6.1Hz, 3H).

Hexyl isopropyl selenide (**12f**)

^{1}H-NMR δ 3.10(m, J=6.8Hz, 1H), 2.58(t, J=7.3Hz, 2H), 1.06-1.94 (m, 8H), 1.40(d, J=6.8Hz, 6H), 0.89(br t, J=6.3Hz, 3H).

Hexyl isobutyl selenide (**12g**)

^{1}H-NMR δ 2.89(m, J=6.8Hz, 1H), 2.58(t, J=7.3Hz, 2H), 1.41(d, J=6.8Hz, 3H), 1.14-1.86(m, 10H), 0.98(t, J=7.3Hz, 3H), 0.89(br t, J=6.1Hz, 3H).

Se-Hexyl selenobenzoate (**12h**)

^{1}H-NMR δ 7.29-8.04(m, 5H, ArH), 3.10(t, J=7.3Hz, 2H), 0.92-1.97 (m, 8H), 0.89(br t, J=6.4Hz, 3H).

Se-Benzyl selenobenzoate (**12i**)

^{1}H-NMR δ 7.20-7.98(m, 5H, ArH), 4.35(s, 2H, benzylic proton).

Se-Hexyl selenocrotonate (**12j**)

^{1}H-NMR δ 6.88(dq, J_1=6.8Hz, J_2=15.4Hz, 1H), 6.14(dq, J_1=1.7Hz, J_2=15.4Hz, 1H), 2.96(t, J=7.3Hz, 2H), 1.85(dd, J_1=1.7Hz, J_2=6.8Hz, 3H), 1.07-1.80(m, 8H), 0.89(br t, J=6.3Hz, 3H)

Se-Hexyl ethyl selenocarbonate (**12k**)

^{1}H-NMR δ 4.30(q, J=7.1Hz, 2H), 2.89(t, J=7.1Hz, 2H), 1.00-1.97 (m, 8H), 1.31(t, J=7.1Hz, 3H), 0.89(br t, J=6.1Hz, 3H).

Se-Benzyl ethyl selenocarbonate (**12l**)

^{1}H-NMR δ 7.10-7.22(m, 5H, ArH), 4.26(q. J=7.1Hz, 2H), 4.05(s, 2H, benzylic proton), 1.31(t, J=7.1Hz, 3H).

Se-Hexyl phenyl selenocarbonate (**12m**)

^{1}H-NMR δ 6.72-7.58(m, 5H, ArH), 2.97(t, J=7.3Hz, 2H), 1.06-2.00 (m, 8H), 0.89(br t, J=6.1Hz, 3H).

Diphenylphosphinothioyl hexyl selenide (**12n**)

^{1}H-NMR δ 7.09-8.15(m, 10H, ArH), 3.00(dt, J_1=12.2Hz, J_2=7.3Hz, 2H), 0.99-1.90(m, 8H), 0.84(br t, J=6.1Hz, 3H).

Crotyl hexyl selenide (**12o**)

^{1}H-NMR δ 5.54-5.77(m, 2H, olefinic proton), 3.13(dd, J_1=1.1Hz, J_2=6.1Hz, 2H), 2.50(t, J=7.3Hz, 2H), 1.00-1.83(m, 11H), 0.89(br t, J=6.1Hz, 3H).

Hexyl propargyl selenide (**12p**)

^{1}H-NMR δ 3.18(d, J=2.7Hz, 2H), 2.78(t, J=7.3Hz, 2H), 2.34(t, J= 2.7Hz, 1H, acetylenic proton), 1.09-1.77(m, 8H), 0.89(br t, J=6.1Hz, 3H).

1-6 References and Notes

(1) Reviews: *Organic Compounds of Sulphur, Selenium, and Tellurium*; Specialist Periodical Reports; The Chemical Society: London, 1970-1981; Vols. 1-6. Paulmier, C. *Selenium Reagents and Intermediates in Organic Synthesis*; Baldwin, J. E., Ed.; Pergamon Press: 1986; pp 58-83. Guziec, Jr., F. S. *Organoselenium Chemistry*; Liotta, D., Ed.; John Wiley & Sons: 1987; pp 277-324. Guziec, Jr., F. S. *The Chemistry of Organic Selenium and Tellurium Compounds*; Patai, S., Ed.; John Wiley & Sons: New York, 1987; Vol. 2; pp 215-273.

(2) Reid, D. H.; Webster, R. G.; McKenzie, S. *J. Chem. Soc., Perkin Trans. 1* 1979, 2334-2339.

(3) (a) Fischer, H.; Zeuner, S.; Riede, J. *Angew. Chem., Int. Ed. Engl.* 1984, *23*, 726-727. (b) Fischer, H.; Gerbing, U.; Riede, J.; Benn, R. *Ibid*. 1986, *25*, 78-79. (c) Fischer, H.; Tiriliomis, A.; Gerbing, U.; Huber, B.; Muller, G. *J. Chem. Soc., Chem. Commun.* 1987, 559-560.

(4) (a) Krafft, G. A.; Meinke, P. T. *J. Am. Chem. Soc.* 1986, *108*, 1314-1315. (b) Meinke, P. T.; Krafft, G. A.; Spencer, J. T. *Tetrahedron Lett.* 1987, *28*, 3887-3890. (c) Meinke, P. T.; Krafft, G. A. *Ibid*. 1987, *28*, 5121-5124. (d) Idem. *J. Am. Chem. Soc.* 1988, *110*, 8671-8679.

(5) (a) Kirby, G. W.; Trethewey, A. N. *J. Chem. Soc., Chem. Commun.* 1986, 1152-1154. (b) Idem. *J. Chem. Soc., Perkin Trans.*

1 1988, 1913-1922.

(6) (a) Nakayama, J.; Akimoto, K.; Niijima, J.; Hoshino, M. Tetrahedron Lett. 1987, 28, 4423-4426. (b) Nakayama, J.; Akimoto, K.; Hoshino, M. J. Phys. Org. Chem. 1988, 1, 53-57. (c) Nakayama, J.; Sugihara, Y. Ibid. 1988, 1, 59-61.

(7) Okuma, K.; Sakata, J.; Tachibana, Y.; Honda, T.; Ohta, H. Tetrahedron Lett. 1987, 28, 6649-6652.

(8) Erker, G.; Hock, R.; Nolte, R. J. Am. Chem. Soc. 1988, 110, 624-625.

(9) (a) Okazaki, R.; Ishii, A.; Inamoto, N. J. Chem. Soc., Chem. Commun. 1986, 71-72. (b) Ishii, A.; Okazaki, R.; Inamoto, N. Bull. Chem. Soc. Jpn. 1987, 60, 1037-1040.

(10) It has been reported that bis(trimethylsilyl) selenide smoothly converts sulfoxides, selenoxides, and telluroxides into sulfides, selenides, and tellurides, respectively. See: Detty, M. R.; Seidler, M. D. J. Org. Chem. 1982, 47, 1354-1356.

(11) From the consideration of hard/soft pairs[12] and also from bond energies estimated for H-O (102 Kcal/mol), H-Se (73 Kcal/mol), Si-O (194 Kcal/mol), and Si-Se (131 Kcal/mol).[13, 14]

(12) Pearson, R. G. Hard and Soft Acids and Bases; Dowden, Hutchinson, & Ross, Inc.: Stroudsburg, PA, 1973.

(13) Huber, K. P.; Herzberg, G. Molecular Spectra and Molecular Structure Constants of Diatomic Molecules; Van Nostrand: New York, 1979.

(14) Gunn, S. R. J. Phys. Chem. 1964, 68, 949-952.

(15) All cycloadducts gave satisfactory IR, NMR, mass spectral data, and elemental analyses.

(16) The side reactions are condensation of cyclopentadiene with aldehydes and trimerization of aldehydes or selenoaldehydes.

(17) Fox, M. A.; Cardone, R.; Kiwiet, N. J. *J. Org. Chem.* 1987, *52*, 1469-1474.

(18) For a review, see: Ager, D. J. *Synthesis* 1984, 384-398.

(19) Baldwin, J. E.; Lopez, R. C. G. *Tetrahedron* 1983, *39*, 1487-1498.

(20) Vedejs, E.; Eberlein, T. H.; Wilde, R. G. *J. Org. Chem.* 1988, *53*, 2220-2226.

(21) Roush, W. R.; Gillis, H. R.; Ko, A. I. *J. Am. Chem. Soc.* 1982, *104*, 2269-2283.

(22) Taber, D. F. *Intramolecular Diels-Alder Reactions and Alder-Ene Reactions*; Springer Verlag: New York, 1984. Ciganek, E. *Org. React.* 1984, *23*, 1-374.

(23) Meinke, P. T.; Krafft, G. A. *Tetrahedron Lett.* 1987, *28*, 5121-5124.

(24) Paulmier, C. *Selenium Reagents and Intermediates in Organic Synthesis*; Baldwin, J. E., Ed.; Pergamon Press: Oxford, 1986. Liotta, D. *Organoselenium Chemistry*; John Wiley & Sons: New York, 1987. *The Chemistry of Organic Selenium and Tellurium Compounds*; Patai, S.; Rappoport, Z., Ed.; John Wiley & Sons: Chichester, 1986-1987; Vols. 1-2. Krief, A.; Hevesi, L. *Organo-*

selenium Chemistry I; Springer-Verlag: Berlin, 1988.

(25) (a) Bird, M. L.; Challenger, F. J. Chem. Soc. 1942, 570. (b) Brandsma, L.; Wigers, H. Recl. Trav. Chim. Pays-Bas 1963, 82, 68. (c) Klayman, D. L.; Griffin, T. S. J. Am. Chem. Soc. 1973, 95, 197. (d) Gladysz, J. A.; Hornby, J. L.; Garbe, J. E. J. Org. Chem. 1978, 43, 1204. (e) Bergman, J.; Engman, L. Synthesis 1980, 569. (f) Sandman, D. J.; Stark, J. C.; Acampora L. A.; Gagne, P. Organometallics 1983, 2, 549. (g) Thompson, D. P.; Boudjouk, P. J. Org. Chem. 1988, 53, 2109.

(26) (a) Bergson, G.; Delin, A. L. Ark. Kemi. 1961, 18, 441; Chem. Abstr. 1962, 57, 11013e. (b) Gunther, W. H. H.; Mautner, H. G. J. Med. Chem. 1964, 7, 229. (c) Clarembeau, M.; Krief, A. Tetrahedron Lett. 1984, 25, 3625. (d) Ley, S. V.; O'Neil, I. A. Low, C. M. R. Tetrahedron 1986, 42, 5363.

(27) (a) Tiecco, M.; Testaferri, L.; Tingoli, M.; Chianelli, D.; Montanucci, M. J. Org. Chem. 1983, 48, 4289. (b) Gulliver, D. J.; Hope, E. G.; Levason, W.; Murray, S. G.; Potter, D. M.; Marshall, G. L. J. Chem. Soc., Perkin Trans. 1 1984, 429.

(28) Gladysz et al. reported that unsymmetrical selenides cannot be synthesized via sequential addition of R^1X and R^2X to Li_2Se and only symmetrical selenides are detected. See Ref. 25.

Chapter 2. Novel Route to Selenoketones from Ketones by the Use of Bis(dimethylaluminum) Selenide

2-1 Introduction

During the past decade, significant interest in the chemistry of highly reactive carbon-heteroatom double bonds has developed. The chemistry of reactive compounds having carbon-selenium double bond also has been actively studied for some years past,[1] with the first synthesis of sterically hindered selenoketones by D. H. R. Barton and co-workers,[2a,b] by Guziec et al.,[2b-m] and by others.[2n-t] Recently, Meinke and Krafft have reported the simple and efficient generation of dienophilic selenoketones via base-induced elimination of cyanide from selenocyanates containing electron-withdrawing or conjugating substituents and its cycloaddition reactions with dienes and dipoles.[3] These methods above mentioned must require the independent preparation of the precursors in many steps from available compounds.

In chapter 1, it has been described that the simple and convenient synthesis of selenoaldehydes via base-catalyzed reaction of aldehydes with bis(trimethylsilyl) selenide, which takes advantage of the large affinity of silicon to oxygen atom.[4] The attempts, however, for the application of this method to the preparation of selenoketones have been unsuccessful. Now it has been found that bis(dimethylaluminum) selenide[5] can serve as an efficient selenating reagent for this purpose. This chapter describes a new method for the direct conversion of ketones to selenoketones, which can be trapped as Diels-Alder adducts, using new selenating reagent, bis(dimethylaluminum) selenide.

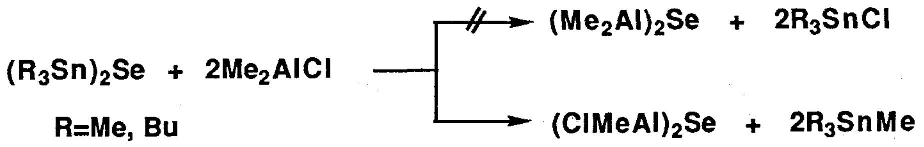
2-2 Synthesis of Bis(dimethylaluminum) Selenide as a New Selenating Reagent

The synthesis of the new reagent, bis(dimethylaluminum) selenide 2, could not be accomplished via the Li_2Se route that was used for the synthesis of bis(trimethylsilyl) selenide 1.[6] However, the transmetallation of 1 with two equivalents of Me_2AlCl in toluene provided an effective alternative route, as shown in eq. 2-1. In fact, the quantitative formation of

$$\underset{1}{(Me_3Si)_2Se} + 2Me_2AlCl \xrightarrow[\text{toluene}]{} \underset{2}{(Me_2Al)_2Se} + \underset{\text{quant.}}{2Me_3SiCl} \qquad (2\text{-}1)$$

chlorotrimethylsilane was confirmed by ^1H-NMR measurement. The reagent 2 in toluene was likely to exist in aggregated from since the reaction mixture turned into a opaque suspension. When the generation of selenoketones was conducted in toluene, the reaction proceeded very slowly probably because of the heterogeneous system. So, after the removal of toluene, THF was added as a solvent to result in a homogeneous system.

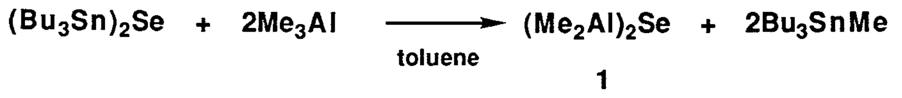
Next, Sn-Al metal exchange by the reaction of bis(tributyltin) selenide **3** with dimethylaluminum chloride was undergone in a similar manner as above-mentioned Si-Al exchange. In toluene the solution likewise became a heterogeneous system with a milky precipitate. To confirm this transmetallation, the reaction was followed by ^{1}H-NMR measurement in Me_3Sn region for the run using bis(trimethyltin) selenide. The signal corresponded to expected trimethyltin chloride (δ 0.66) was not appeared with decreasing the signal of bis(trimethyltin) selenide, but the quantitative formation of tetramethyltin was observed (eq. 2-2). Accordingly, the net selenating reagent formed by the transmetallation of **3** with Me_2AlCl would be bis(chloromethylaluminum) selenide, $(ClMeAl)_2Se$. By virtue of this result, it was predictable that bis(dimethylaluminum)



$$\begin{tikzcd}[column sep=small] & (Me_2Al)_2Se + 2R_3SnCl \\ \begin{array}{c}(R_3Sn)_2Se + 2Me_2AlCl \\ R{=}Me,\ Bu\end{array} \arrow[ur, "/\!/" marking] \arrow[dr] & \\ & (ClMeAl)_2Se + 2R_3SnMe \end{tikzcd} \qquad (2\text{-}2)$$

selenide **2** is also synthesized by the transmetallation of **3** with trimethylaluminum, as shown in eq. 2-3. In fact, the quantitative formation of tetramethyltin was confirmed by ^{1}H-NMR measurement for the run using bis(trimethyltin) selenide

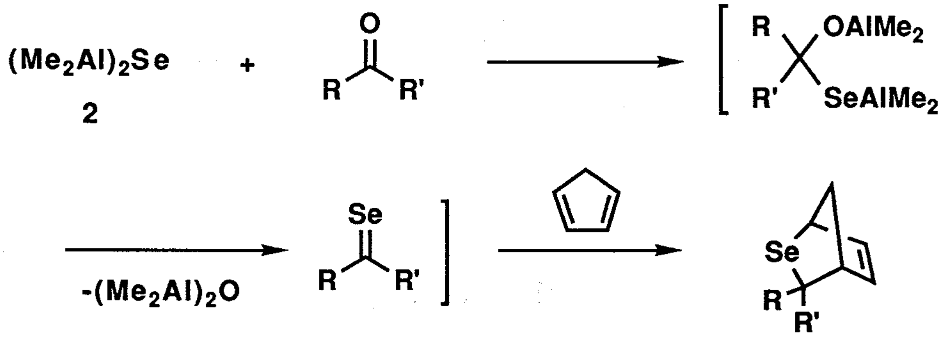
(Scheme 2-1).



$$(Bu_3Sn)_2Se + 2Me_3Al \xrightarrow[\text{toluene}]{} \underset{\mathbf{1}}{(Me_2Al)_2Se} + 2Bu_3SnMe \qquad (2\text{-}3)$$

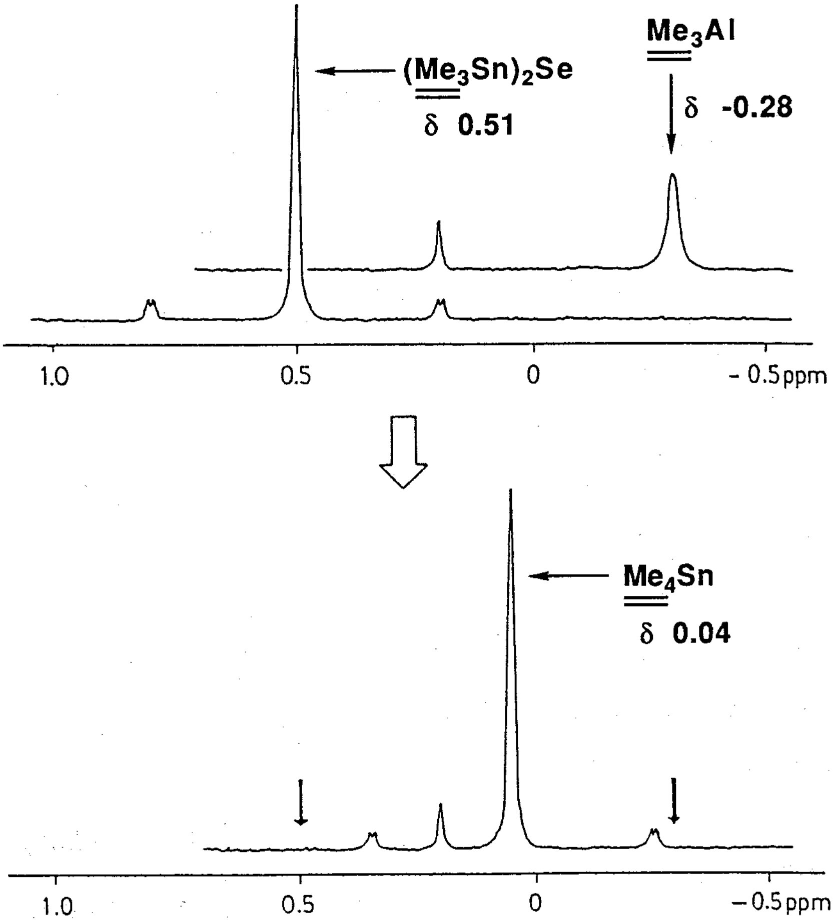
2-3 Reaction of Ketones with Bis(dimethylaluminum) Selenide in the Presence of a Diene

In section 2-2, two methods for the synthesis of 2 were described. Both methods were carried out for the generation of selenoketones. First, using 2 prepared by the transmetallation of 1 with Me_2AlCl in toluene, the conversion of ketones to selenoketones was investigated. After the removal of toluene, the reaction of 2 with a ketone in refluxing THF in the presence of cyclopentadiene in excess gave a cycloadduct of the corresponding selenoketones in moderate to good yields (eq. 2-4). The results of these Diels-Alder reaction are summarized in Table 2-1.



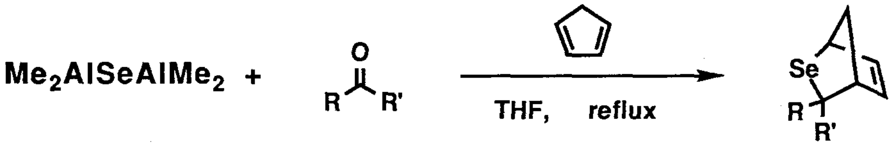
(2-4)

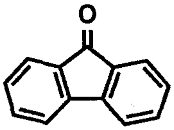
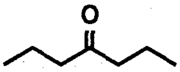
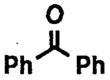
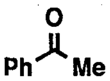
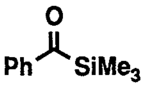
$$(Me_3Sn)_2Se + 2\,Me_3Al \xrightarrow{-\,2\,Me_4Sn} Me_2AlSeAlMe_2$$



Scheme 2-1

Table 2-1. Generation and Trapping of Selenoketones in the Presence of Cyclopentadiene Using 2 formed via Si-Al Metal Exchange



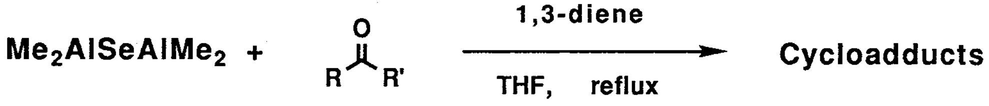
entry	RR'C=O	time (h)	yield[a] (%)
1		17	77
2		17	63
3		18	53
4		19	55
5		13	20
6		14	32 (endo:exo=1:1)[b]
7		14	72 (endo:exo=1:1)[b]

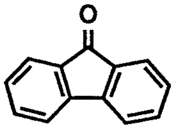
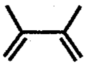
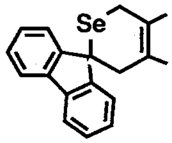
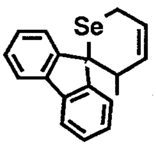
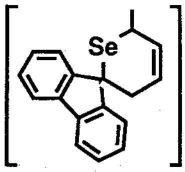
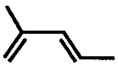
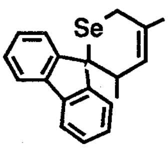
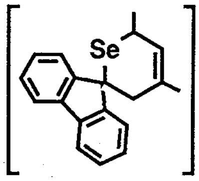
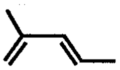
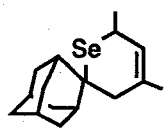
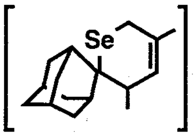
[a] Isolated yield. [b] Determined by ^{1}H-NMR.

The cycloadduct of selenofluorenone and cyclopentadiene was obtained in 77% yield. It is especially noteworthy that even simple ketones can react with **2** in the presence of cyclopentadiene to afford cycloadducts of simple selenoketones in moderate yields (entries 3-6). Moreover, when benzoylsilane was used as a starting ketone, the Diels-Alder reaction of selenobenzoylsilane,[7] an interesting new class of compounds which have not been reported because of the difficulty of preparation, proceeded efficiently to give the cycloadduct, although less stereoselectively (entry 7).

On the other hand, selenofluorenone and selenoadamantanone reacted with an acyclic 1,3-diene, trans-1,3-pentadiene and trans-2-methyl-1,3-pentadiene, to give only one isomer with a complete cycloaddition regioselectivity (entries 9-11 in Table 2-2). However, the Diels-Alder reaction of selenofluorenone and selenoadamantanone proceeded in the opposite regioselectivity. The regiochemistry of selenofluorenone cycloadducts was deduced from the chemical shifts in ^{1}H-NMR spectra. Unusually high field signal at δ 0.45 or 0.40 in the ^{1}H-NMR spectrum of cycloadduct of selenofluorenone and 2-methyl-1,3-pentadiene or 1,3-pentadiene, respectively, would be due to shielding of the methyl protons by the surrounding aromatic ring. Therefore, the methyl group must be adjacent to fluorenyl group as shown in Table 2-2. These regiochemical results are cocsistent with Krafft's results.[3a]

Table 2-2. Generation and Trapping of Selenoketones in the Presence of Acyclic 1,3-Diene Using 2 formed via Si-Al Metal Exchange



entry	RR'C=O	diene	adduct	yield[a] (%)
8				53
9			  none seen	65
10			  none seen	58
11			  none seen	26

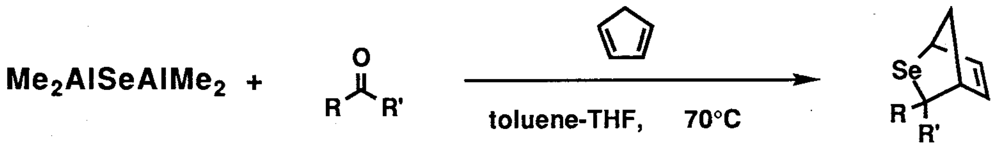
[a] Isolated yield.

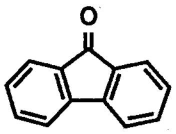
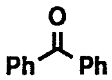
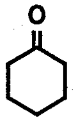
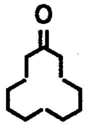
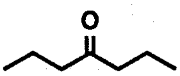
Next, the reaction of ketones with 2 prepared by the Sn-Al metal exchange (eq. 2-3) was carried out in the presence of a diene. These results of cycloaddition of selenoketones with cyclopentadiene and an acyclic 1,3-diene are summarized in Tables 2-3 and 2-4, respectively. The yield of the cycloadducts was remarkably improved and many ketones were converted into the corresponding selenoketones, compared with the results of Si-Al exchange method. The regiochemical results on the Diels-Alder reaction of selenoketones generated by this method are listed in Table 2-5. In aromatic and aliphatic selenoketone cycloaddition reactions, the different regioselectivity was observed.

In the absence of a diene, 2 reacted with diphenylcyclopropenone to give a dimer of diphenylselenocyclopropenone in 83% yield as an orange crystal (eq. 2-5). The mass spectrum of this compound supported the dimeric molecular formula of $C_{30}H_{20}Se_2$ with a molecular ion at m/e=540 (Se^{80}) having the expected isotope pattern for Se_2. On the other hand, the reaction of 2 with fluorenone under the similar condition gave 9,9'-bifluorene, formed by reductive coupling with the elimination of selenium, in 52% yield (eq. 2-6). The structure of this compound was confirmed by comparison with the authentic sample in ^{1}H-NMR spectrum and melting point.

After various attempts for isolation of a selenoketone by the present new procedures, we have succeeded in the isolation

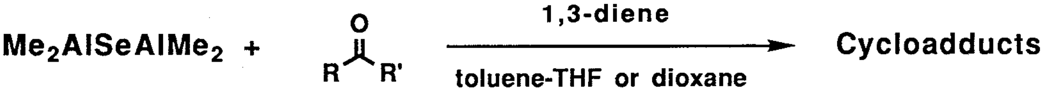
Table 2-3. Generation and Trapping of Selenoketones in the Presence of Cyclopentadiene Using 2 formed via Sn-Al Metal Exchange



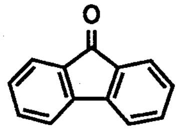
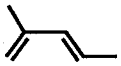
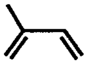
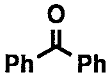
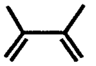
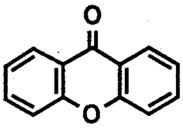
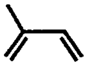
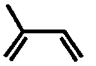
entry	RR'C=O	time (h)	yield[a] (%)
1		5.5	97
2		6.0	70
3		6.5	87
4		6.0	60
5		6.5	57
6		8.0	70
7		6.0	78

[a] Isolated yield.

Table 2-4. Generation and Trapping of Selenoketones in the Presence of Acyclic 1,3-Diene Using 2 formed via Sn-Al Metal Exchange



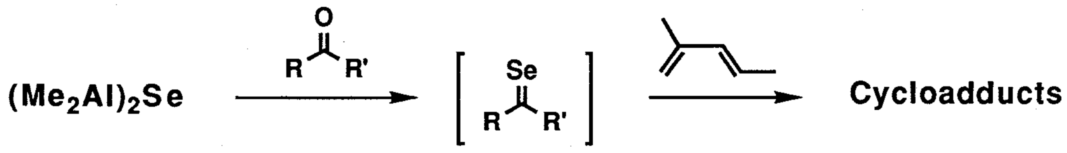
$$Me_2AlSeAlMe_2 + RC(=O)R' \xrightarrow[\text{toluene-THF or dioxane}]{\text{1,3-diene}} \text{Cycloadducts}$$

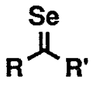
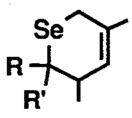
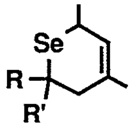
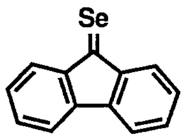
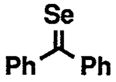
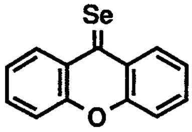
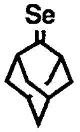
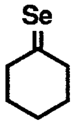
entry	RR'C=O	diene	temp.[a] (°C)	time (h)	yield[b] (%)
8			70	6	78
9			70	6	75
10			100	6	85
11			70	6	82
12			100	7	71
13			100	22	88
14			70	21	62
15			100	21	46
16			70	6	35
17			100	7	33

[a] Toluene-THF: 70°C, Toluene-Dioxane: 100°C.

[b] Isolated yield.

Table 2-5. Regiochemistry of Diels-Alder Reaction of Selenoketones with 2-Methyl-1,3-pentadiene

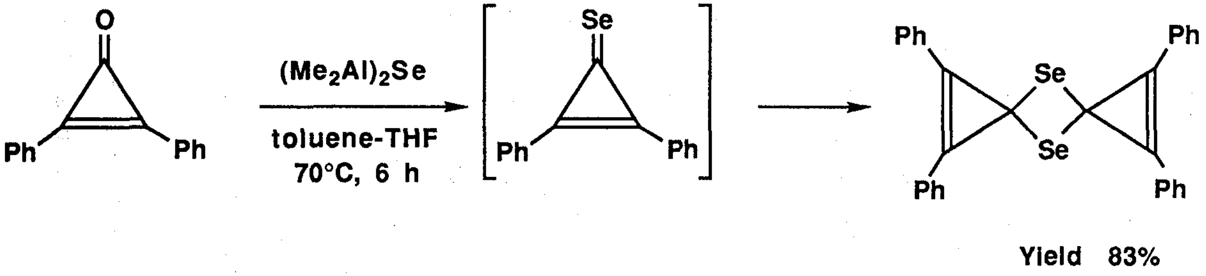


		:	 [a]
	> 99	:	1
	91	:	9
	84	:	16
	1	:	> 99
	1	:	> 99
	11	:	89

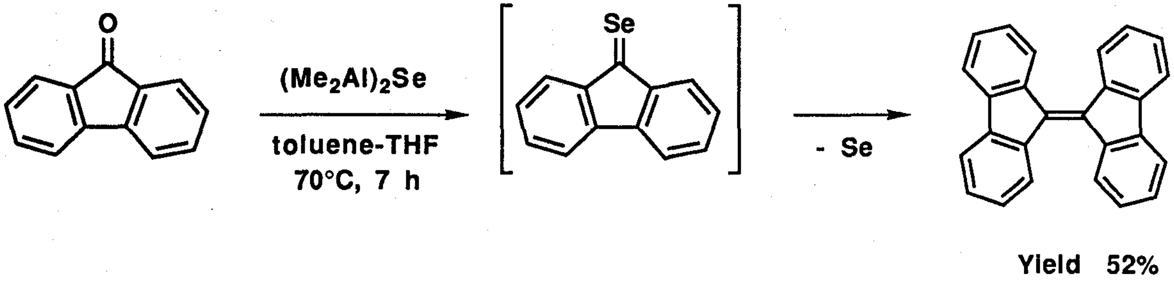
[a] Determined by ^{1}H-NMR.

of a sterically hindered selenoketone. Thus, selenofenchone which showed the characteristic blue color was prepared in 32% yield directly from fenchone using refluxing toluene as the solvent (eq. 2-7).

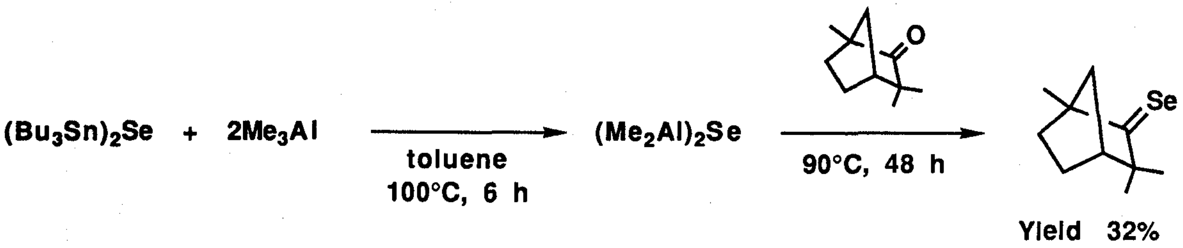
The described method using bis(dimethylaluminum) selenide 2 opens a new and general route to selenoketones. The application to the other selenocarbonyl compounds, as well as the use of 2 as a novel selenating reagent, will be investigated.


O
Ph
Ph
(Me$_2$Al)$_2$Se
toluene-THF
70°C, 6 h
Se
Ph
Ph
Ph
Se
Se
Ph
Ph
Ph
Yield 83%

(2-5)


O
(Me$_2$Al)$_2$Se
toluene-THF
70°C, 7 h
Se
- Se
Yield 52%

(2-6)


(Bu$_3$Sn)$_2$Se + 2Me$_3$Al
toluene
100°C, 6 h
(Me$_2$Al)$_2$Se
O
90°C, 48 h
Se
Yield 32%

(2-7)

2-4 Experimental

Apparatus

Melting points were recorded on a Yanagimoto MP-S2 melting point apparatus. Melting points are uncorrected. Infrared spectra were obtained on a JASCO A-202 spectrometer and absorptions are reported in reciprocal centimeters. ^{1}H-NMR spectra were determined on a JEOL JX-100F spectrometer at 100 MHz and are reported in parts per million (δ) downfield from internal tetramethylsilane (TMS) in $CDCl_3$. Mass spectra were recorded on a Hitachi M-80 spectrometer.

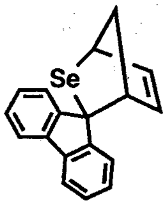
Materials

Tetrahydrofuran (THF) was freshly distilled from potassium /benzophenone just prior to use. Super Hydride® and chloroform-d were purchased from Aldrich Chemicals, Ltd. and used without purification. Dimethylaluminum chloride and trimethylaluminum were purchased from Kanto Chemical Co., Inc. and used without purification. Metallic selenium (99.999%) was purchased from Nakarai Chemicals, Ltd. Cyclopentadiene was obtained by heating (160-180 °C) technical dicyclopentadiene carefully under a fractionating column. The other dienes, ketones, organosilicon, and organotin compounds were purchased from commercial sources and purified by distillation or recrystallization.

General Procedure for the Generation and Trapping of Selenoketones Using Bis(dimethylaluminum) Selenide

A typical experimental procedure is exemplified by the synthesis of a selenofluorenone cycloadduct. Trimethylaluminum (1.0 M solution in hexane, 2.2 mL, 2.2 mmol) was added to a solution of bis(tributyltin) selenide (659 mg, 1.0 mmol), bp 163-166 °C (0.1 mmHg), easily prepared by the reaction of Li_2Se and $n\text{-}Bu_3SnCl$, in toluene (15 mL) under argon and the mixture was stirred for 15 h at 100 °C. After the removal of toluene carefully under reduced pressure, THF (20 mL) as solvent, cyclopentadiene (660 mg, 10 mmol), and fluorenone (216 mg, 1.2 mmol) were added in that order to the residue. The mixture was subsequently heated under reflux for 5.5 h and then worked up with water. After extraction with ether, the combined extracts were dried, concentrated, and purified by flash column chromatography on silica gel (hexane:dichloromethane=2:1 as eluent) to give the selenofluorenone cycloadduct (300 mg, 97% yield).

Spiro[9H-fluorene-9',3'-2'-selenabicyclo[2.2.1]hept-5'-ene]

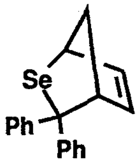


Mp 104-105 °C.

^{1}H-NMR δ 7.06-7.76(m, 8H, ArH), 6.82(dd, J_1=2.9Hz, J_2=5.4Hz, 1H, C-6), 6.02(dd, J_1=3.2Hz, J_2=5.4Hz, 1H, C-5), 4.82 (br s, 1H, C-1), 2.79-2.88(m, 2H, C-4 and C-7), 2.03 (dt, J_1=10.2Hz, J_2=2.4Hz, 1H, C-7).

MS, m/e(relative intensity) 244(100), 163(61), 152(30), 66 (64).

3,3-Diphenyl-2-selenabicyclo[2.2.1]hept-5-ene



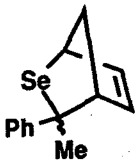
Mp 123.5-124.5 °C.

^{1}H-NMR δ 7.11-7.39(m, 10H, ArH), 6.43(dd, J_1=2.9Hz, J_2=5.4Hz, 1H, C-6), 5.37(dd, J_1=2.9Hz, J_2=5.4Hz, 1H, C-5), 4.57 (br s, 1H, C-1), 3.79(br s, 1H, C-4), 2.35(d, J=9.5Hz, 1H, C-7), 2.12(dt, J_1=9.5Hz, J_2=2.7Hz, 1H, C-7).

MS, m/e(relative intensity) 312(M^+, 3), 246(100), 244(51), 215(6), 165(76), 66(14).

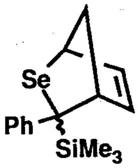
3-Methyl-3-phenyl-2-selenabicyclo[2.2.1]hept-5-ene

(endo:exo=50:50)



^{1}H-NMR δ 6.55(dd, J_1=2.9Hz, J_2=5.6Hz, 1H), 6.27(dd, J_1=2.9Hz, J_2=5.6Hz, 1H), 6.05(dd, J_1=3.9Hz, J_2=5.6Hz, 1H), 5.57 (dd, J_1=3.9Hz, J_2=5.6Hz, 1H), 4.43(br s, 1H), 3.31(br s, 1H), 3.21(br s, 1H), 2.11(s, 3H), 1.73(s, 3H), 1.92 -2.22(m, 2H).

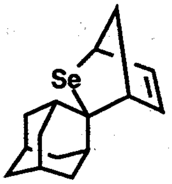
3-Phenyl-3-trimethylsilyl-2-selenabicyclo[2.2.1]hept-5-ene (endo:exo=50:50)



^{1}H-NMR δ 6.40(dd, J_1=2.7Hz, J_2=5.4Hz, 1H), 6.21(dd, J_1=2.7Hz, J_2=5.4Hz, 1H), 5.89(dd, J_1=3.4Hz, J_2=5.4Hz, 1H), 5.66 (dd, J_1=3.4Hz, J_2=5.4Hz, 1H), 4.37(br s, 1H), 3.81(br s, 1H), 1.53-2.03(m, 2H), 0.07(s, 9H), -0.03(s, 9H).

MS, m/e(relative intensity) 308(M^+, 4), 242(8), 227(14), 155 (100), 135(23), 73(100).

Spiro[adamantane-2,3'-2'-selenabicyclo[2.2.1]hept-5'-ene]



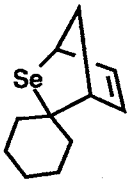
Mp 44-45.5 °C.

^{1}H-NMR δ 6.38(dd, J_1=2.9Hz, J_2=5.6Hz, 1H, C-6), 5.86(dd, J_1= 2.9Hz, J_2=5.6Hz, 1H, C-5), 4.22(br s, 1H, C-1), 3.29

(br s, 1H, C-4), 1.54-2.33(m, 16H).

MS, m/e(relative intensity) 280(M^+, 21), 214(40), 199(100), 133(18), 91(13), 79(10).

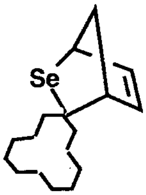
Spiro[cyclohexane,3'-2'-selenabicyclo[2.2.1]hept-5'-ene]



^{1}H-NMR δ 6.37(dd, J_1=2.9Hz, J_2=5.4Hz, 1H, C-6), 5.84(dd, J_1=3.2Hz, J_2=5.4Hz, 1H, C-5), 4.24(br s, 1H, C-1), 2.62 (br s, 1H, C-4), 1.04-2.38(m, 12H).

MS, m/e(relative intensity) 228(M^+, 28), 162(28), 148(23), 147(100), 119(13), 105(25), 81(69).

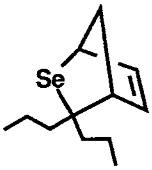
Spiro[cyclododecane,3'-2'-selenabicyclo[2.2.1]hept-5'-ene]



^{1}H-NMR δ 6.36(dd, J_1=2.9Hz, J_2=5.4Hz, 1H, C-6), 5.84(dd, J_1=3.2Hz, J_2=5.4Hz, 1H, C-5), 4.25(br s, 1H, C-1), 2.70 (br s, 1H, C-4), 1.18-2.17(m, 24H).

MS, m/e(relative intensity) 312(M^+, 41), 231(100), 135(16), 109(34), 95(32), 91(54), 83(57).

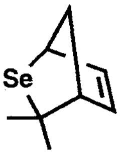
3,3-Di-n-propyl-2-selenabicyclo[2.2.1]hept-5-ene



^{1}H-NMR δ 6.35(dd, J_1=2.7Hz, J_2=5.4Hz, 1H, C-6), 5.82(dd, J_1=3.4Hz, J_2=5.4Hz, 1H, C-5), 4.26(br s, 1H, C-1), 2.72 (br s, 1H, C-4), 0.82-2.17(m, 16H).

MS, m/e(relative intensity) 244(M^+, 13), 178(12), 163(100), 122(47), 121(78).

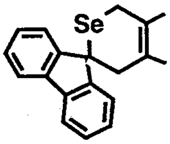
3,3-Dimethyl-2-selenabicyclo[2.2.1]hept-5-ene



^{1}H-NMR δ 6.39(dd, J_1=2.9Hz, J_2=5.6Hz, 1H, C-6), 5.91(dd, J_1=3.4Hz, J_2=5.6Hz, 1H, C-5), 4.33(br s, 1H, C-1), 2.50 (br s, 1H, C-4), 2.09(d, J=9.3Hz, 1H, C-7), 1.76-1.95 (m, 1H, C-7), 1.78(s, 3H, Me), 1.38(s, 3H, Me).

MS, m/e(relative ntensity) 188(M^+, 7), 158(5), 122(7), 108 (26), 107(100), 106(25), 93(44), 91(53).

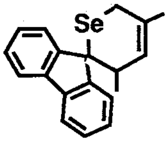
3',6'-Dihydro-4',5'-dimethyl-spiro[9H-fluorene-9,2'-[2'H]-selenopyran]



Mp 104.5-105.5 °C.

^{1}H-NMR δ 7.67-7.76(m, 2H, ArH), 7.25-7.53(m, 6H, ArH), 3.54 (br s, 2H, C-6), 2.66(br s, 2H, C-3), 2.02(br s, 3H, Me), 1.76(br s, 3H, Me).

3',6'-Dihydro-3',5'-dimethyl-spiro[9H-fluorene-9,2'-[2'H]-selenopyran

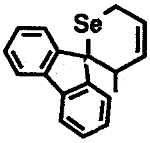


Mp 158-159 °C.

^{1}H-NMR δ 7.14-7.81(m, 8H, ArH), 5.60(br s, 1H, C-4), 3.38-3.54(m, 1H, C-3), 3.63(d, J=16.4Hz, 1H, C-6), 3.29(d, J=16.4Hz, 1H, C-6), 2.01(br s, 3H, C5-Me), 0.45(d, J=7.1Hz, 3H, C3-Me).

MS, m/e(relative intensity) 326(M^+, 27), 244(100), 242(51), 165(31).

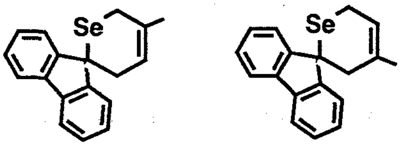
3',6'-Dihydro-3'-methyl-spiro[9H-fluorene-9,2'-[2'H]-selenopyran]



^{1}H-NMR δ 7.14-7.73(m, 8H, ArH), 5.75-6.07(m, 2H, C-4,5), 3.41-3.64(m, 3H, C-3,6,6), 0.40(d, J=7.1Hz, 3H, C3-Me).

MS, m/e(relative intensity) 312(M^+, 26), 244(100), 215(53).

3',6'-Dihydro-5'-methyl-spiro[9H-fluorene-9,2'-[2'H]-selenopyran] and 3',6'-Dihydro-4'-methyl-spiro[9H-fluorene-9,2'-[2'H] selenopyran] (59:41)

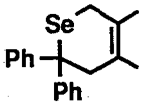


Mp 93.5-94.5 °C.

^{1}H-NMR δ 7.21-7.78(m, 8H, ArH), 5.70-6.02(m, 1H, olefinic proton), 3.50(br s), 3.56-3.70(m), 2.68-2.84(m), 2.61 (br s), 2.03, 1.84(3H, Me).

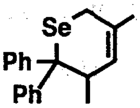
MS, m/e(relative intensity) 312(M^+, 42), 244(59), 231(100), 216(41), 215(30).

3,6-Dihydro-4,5-dimethyl-2,2-diphenyl-2H-selenopyran



^{1}H-NMR δ 7.17-7.29(m, 10H, ArH), 2.96(br s, 2H, C-6), 2.86 (br s, 2H, C-3), 1.73(br s, 6H, C-4,5).

3,6-Dihydro-3,5-dimethyl-2,2-diphenyl-2H-selenopyran (major)

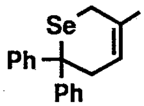


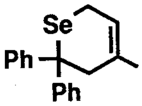
Mp 100-101.5 °C.

^{1}H-NMR δ 7.09-7.51(m, 10H, ArH), 5.67(d, J=5.4Hz, 1H, C-4), 2.57-3.01(m, 3H, C-3,6,6), 1.73(br s, 3H, C5-Me), 0.83 (d, J=6.8Hz, 3H, C3-Me).

MS, m/e(relative intensity) 328(M$^+$, 17), 247(41), 246(100), 244(30), 165(19), 91(13).

3,6-Dihydro-2,2-diphenyl-5-methyl-2H-selenopyran and 3,6-Dihydro-2,2-diphenyl-4-methyl-2H-selenopyran (64:36)

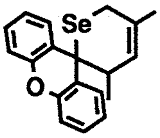




^{1}H-NMR δ 7.16-7.45(m, 10H, ArH), 5.50-5.79(m, 1H, olefinic proton), 2.81-3.14(m), 2.86(d, J=8.8Hz), 1.74, 1.82(br s, 3H, Me).

MS, m/e(relative intensity) 314(M$^+$, 22), 246(18), 234(48), 233(100), 205(10), 165(15), 155(15), 91(43).

3',6'-Dihydro-3',5'-dimethyl-spiro[9H-xanthene-9,2'-[2'H]-selenopyran] (major isomer)

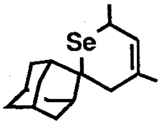


^{1}H-NMR δ 7.03-7.81(m, 8H, ArH), 5.46-5.60(m, 1H, C-4), 3.14-3.57(m, 1H, C-3), 3.55(d, J=15.0Hz, 1H, C-6), 3.12(d,

J=15.0Hz, 1H, C-6), 1.98(br d, J=1.7Hz, 3H, C5-Me), 0.87(d, J=7.1Hz, 3H, C3-Me).

MS, m/e(relative intensity) 342(M^+, 1), 261(50), 260(40), 208 (100), 207(99), 197(87), 181(24), 82(16).

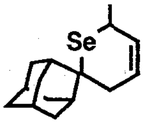
3',6'-Dihydro-4',6'-dimethyl-spiro[adamantane-2,2'-[2'H]-selenopyran]



^{1}H-NMR δ 5.46-5.49(m, 1H, C-5), 3.54-3.86(m, 1H, C-6), 2.82 (d, J=15.1Hz, 1H, C-3), 1.84(br s, 3H, C4-Me), 1.43(d, J=7.1Hz, 3H, C6-Me), 1.56-2.39(m, 15H).

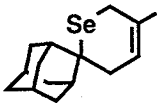
MS, m/e(relative intensity) 296(M^+, 21), 216(18), 215(100), 135(10), 133(8).

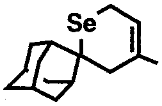
3',6'-Dihydro-6'-methyl-spiro[adamantane-2,2'-[2'H]-selenopyran]



^{1}H-NMR δ 5.30-5.84(m, 2H, C-4,5), 3.64-3.74(m, 1H, C-6), 3.07 -3.15(m, 1H, C-3), 2.77(dd, J_1=1.7Hz, J_2=4.9Hz, 1H, C-3), 1.34-2.53(m, 14H), 1.46(d, J=7.3Hz, 3H, C6-Me).

3',6'-Dihydro-5'-methyl-spiro[adamantane-2,2'-[2'H]-selenopyran] and 3',6'-Dihydro-4'-methyl-spiro[adamantane-2,2'-[2'H]-selenopyran] (50:50)

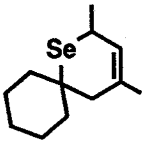




^{1}H-NMR δ 3.74-4.09(m, 1H, olefinic proton), 2.97-3.26(m), 2.54-2.71(br s), 1.51-2.51(m, 14H), 1.81(br s, 3H, Me).

MS, m/e(relative intensity) 282(M^+, 13), 235(24), 214(32), 201(100), 135(16), 133(25).

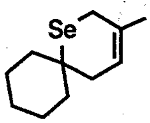
3',6'-Dihydro-4',6'-dimethyl-spiro[cyclohexane,2'-[2'H]-selenopyran]

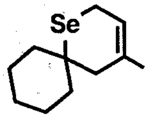


^{1}H-NMR δ 5.37-5.41(m, 1H, C-5), 3.46-3.79(m, 1H, C-6), 0.82-2.40(m, 12H), 1.77(br s, 3H, C4-Me), 1.42(d, J=7.1Hz, 3H, C6-Me).

MS, m/e(relative intensity) 244(M^+, 39), 216(17), 163(81), 161(38), 139(20), 107(21), 81(100).

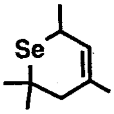
3',6'-Dihydro-5'-methyl-spiro[cyclohexane,2'-[2'H]-selenopyran] and 3',6'-Dihydro-4'-methyl-spiro[cyclohexane,2'-[2'H]-selenopyran] (60:40)





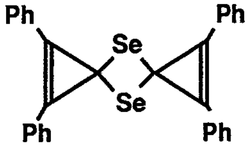
^{1}H-NMR δ 5.43-5.69(m, 1H, olefinic proton), 3.09-3.21(m), 3.03(br s), 2.23-2.31(m), 2.17(br s), 1.22-2.02(m, 13H).

3,6-Dihydro-2,2,4,6-tetramethyl-2H-selenopyran (major isomer)



^{1}H-NMR δ 5.20-5.49(m, 1H, C-5), 3.60-3.91(m, 1H, C-6), 1.87-2.44(m, 2H, C-3), 1.75(br s, 3H, C4-Me), 1.44(d, J=7.1 Hz, 3H, C6-Me), 1.48(s, 3H, C2-Me), 1.42(s, 3H, C2-Me).

Dimer of diphenylselenocyclopropenone

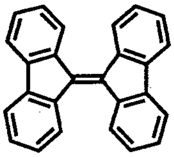


Mp 140-141 °C. Orange crystal.

^{1}H-NMR δ 8.23-8.33(m, 8H), 7.60-7.82(m, 12H).

MS, m/e(relative intensity) 540(M^+, 1), 270(100), 189(32), 178(32), 165(46).

9,9'-Bifluorene

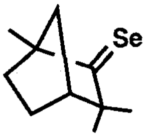


Mp 194-195 °C. Orange crystal.

^{1}H-NMR δ 8.33-8.42(m, 4H), 7.66-7.74(m, 4H), 7.11-7.41(m, 8H)

MS, m/e(relative intensity) 328(M$^+$, 17), 244(9), 165(100).

Selenofenchone



Mp 40-45 °C. Blue crystal.

^{1}H-NMR δ 2.43(br s, 1H), 1.16-1.94(m, 6H), 1.46(s, 3H), 1.24 (s, 3H), 1.17(s, 3H).

IR (NaCl, neat) 1080, 1045 cm^{-1}.

VIS-UV (cyclohexane) 622, 272, 212 nm.

2-5 References and Notes

(1) Paulmier, C. Selenium Reagent and Intermediates in Organic Synthesis; Baldwin, J. E., Ed.; Pergamon Press: 1986; pp 58-83. Guziec, Jr., F. S. Organoselenium Chemistry; Liotta, D., Ed.; John Wiley & Sons: 1987; pp 277-324. Guziec, Jr., F. S. The Chemistry of Organic Selenium and Tellurium Compounds; Patai, S., Ed.; John Wiley & Sons: 1987; Vol. 2; pp 215-273.

(2) (a) Back, T. G.; Barton, D. H. R.; Britten-Kelly, M. R.; Guziec, Jr., F. S. J. Chem. Soc., Chem. Commun. 1975, 539. (b) Idem. J. Chem. Soc., Perkin Trans. 1 1976, 2079. (c) Cullen, E. R.; Guziec, Jr., F. S.; Murphy, C. J.; Wong, T. C.; Andersen, K. K. J. Chem. Soc., Perkin Trans. 2 1982, 473. (d) Andersen, K. K.; Gash, D. M.; Robertson, J. D.; Guziec, Jr., F. S. Tetrahedron Lett. 1982, 23, 911. (e) Wong, T. C.; Guziec, Jr., F. S. Moustakis, C. A. J. Chem. Soc., Perkin Trans. 2 1983, 1471. (f) Wong, T. C.; Ang, T. T.; Guziec, Jr., F. S.; Moustakis, C. A. J. Magn. Reson. 1984, 57, 463. (g) Guziec, Jr., F. S.; Russo, J. M. Synthesis 1984, 479. (h) Guziec, Jr., F. S.; Moustakis, C. A. J. Chem. Soc., Chem. Commun. 1984, 63. (i) Guziec, Jr., F. S.; SanFilippo, L. J.; Murphy, C. J.; Moustakis, C. A.; Cullen, E. R. Tetrahedron 1985, 41, 4843. (j) Guziec, Jr., F. S.; Murphy, C. J.; Cullen, E. R. J. Chem. Soc., Perkin Trans. 1 1985, 107. (k) Cullen, E. R.; Guziec, Jr., F. S.; Murphy, C. J. Wong, T. C.; Andersen, K. K. J. Am. Chem. Soc. 1981, 103, 7055.

(l) Cullen, E. R.; Guziec, Jr., F. S.; Hollander, M. I.; Murphy C. J. *Tetrahedron Lett.* 1981, **22**, 4563. (m) Cullen, E. R.; Guziec, Jr., F. S.; Murphy, C. J. *J. Org. Chem.* 1982, **47**, 3563. (n) Okazaki, R.; Ishii, A.; Fukuda, N.; Oyama, H.; Inamoto, N. *J. Chem. Soc., Chem. Commun.* 1982, 1187. (o) Okazaki, R.; Ishii A.; Inamoto, N. *Ibid.* 1983, 1429. (p) Steliou, K.; Mrani, M. *J. Am. Chem. Soc.* 1982, **104**, 3104. (q) Nakayama, J.; Akimoto, K.; Niijima, J.; Hoshino, M. *Tetrahedron Lett.* 1987, **28**. 4423. (r) Nakayama, J.; Akimoto, K.; Hoshino, M. *J. Phy. Org. Chem.* 1988, **1**, 53. (s) Nakayama, J.; Sugihara, Y. *Ibid.* 1988, **1**, 59. (t) Okuma, K.; Yamasaki, Y.; Komiya, T.; Kodera, Y.; Ohta, H. *Tetrahedron Lett.* 1987, **28**, 6659.

(3) (a) Meinke, P. T.; Krafft, G. A. *Tetrahedron Lett.* 1987, **28**, 3887. (b) Idem, *J. Am. Chem. Soc.* 1988, **110**, 8679.

(4) (a) Segi, M.; Nakajima, T.; Suga, S.; Murai, S.; Ryu, I.; Ogawa, A.; Sonoda, N. *J. Am. Chem. Soc.* 1988, **110**, 1976. (b) Segi, M.; Takahashi, M.; Nakajima, T.; Suga, S.; Murai, S.; Sonoda, N. *Tetrahedron Lett.* 1988, **29**, 6965.

(5) Systematic name is tetramethyl-μ-selenoxodialuminum.

(6) Detty, M. R.; Seidler, M. D. *J. Org. Chem.* 1982, **47**, 1354.

(7) Recently, Diels-Alder reaction of sulfur analogue, thiobenzoylsilane, with dienes was reported. (a) Bonini, B. F.; Lenzi, A.; Maccagnani, G. *J. Chem. Soc., Perkin Trans. 1* 1987, 2643. (b) Ricci, A.; Degl'Innocent, A.; Capperucci, A.; Reginato, G. *J. Org. Chem.* 1989, **54**, 19.

Chapter 3. Generation and Reactions of Thioaldehydes

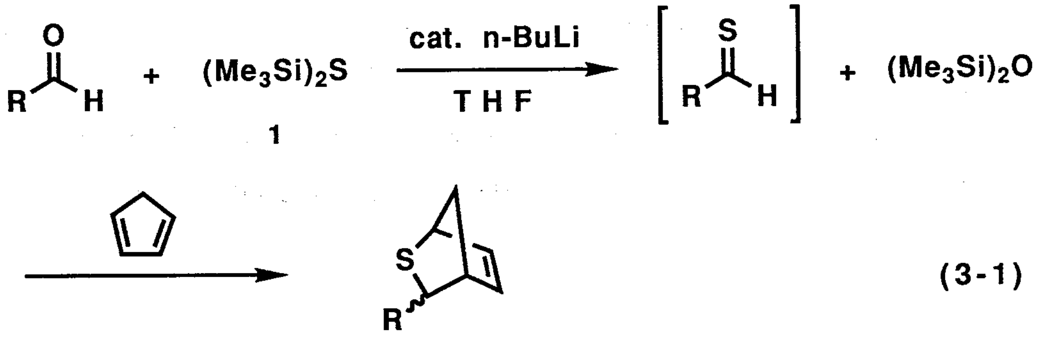
3-1 Introduction

Thiocarbonyl-containing compounds have been known to serve as an important intermediate in organic synthesis and widely employed in organic reactions.[1] One of those, thioaldehydes,[2] would appear especially well suited as heterodienophiles in organic synthesis since (i) the thial π-bond is weak and should be reactive in cycloadditions and (ii) sulfur may be removed from the cycloadducts or retained and used to facilitate further transformations. However, simple thioaldehydes are too reactive to allow their isolation of manipulation at ambient temperatures. Stabilization of thioaldehydes by strongly electron-donating groups[3] or by steric protection[4] has been known, but the reactivity of the thial group is correspondingly diminished. Vedejs et al. have widely investigated the generation and the Diels-Alder reactions of thioaldehydes by the photochemical method from phenacyl sulfide derivatives.[5] Several methods for thioaldehyde generation have been developed since then.[6]

In chapter 1 the simple and convenient method which allows the direct conversion of aldehydes to selenoaldehydes was described.[7] This concept can also be applicable to the preparation of thioaldehydes. Thus, bis(trimethylsilyl) sulfide was used as a sulfurating reagent of aldehydes, which takes advantage of the large affinity of silicon to oxygen atom. This chapter describes general and simple synthesis of thioaldehydes and their reactions.

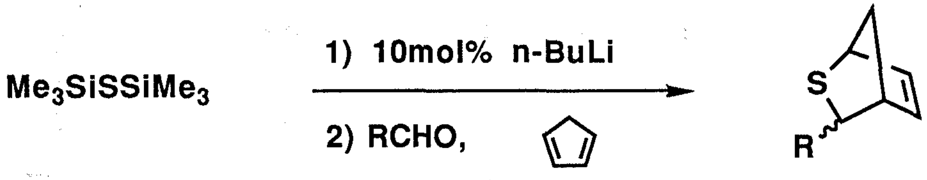
3-2 Generation and Diels-Alder Reaction of Thioaldehydes Using Bis(trimethylsilyl) Sulfide under Base-catalyzed Condition

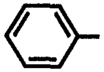
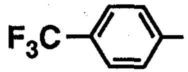
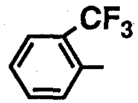
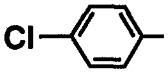
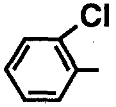
The reaction of bis(trimethylsilyl) sulfide **1**[8] with a variety of aldehydes in the presence of a catalytic amount of butyllithium and excess cyclopentadiene to give the cycloadducts of the corresponding thioaldehydes and the diene (eq. 3-1). This method for the thioaldehyde synthesis is widely applicable to many aromatic and aliphatic aldehydes. The results of Diels-Alder reaction with cyclopentadiene are summarized in Tables 3-1 and 3-2. All cycloadducts gave satisfactory IR, NMR, mass spectral data, and elemental analyses. Aromatic



(3-1)

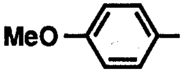
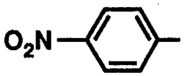
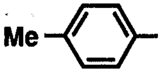
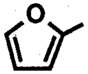
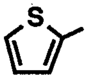
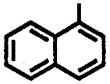
Table 3-1. Generation and Trapping of Aromatic Thioaldehydes in the Presence of Cyclopentadiene



RCHO R=	temp. (°C)	time (h)	yield[a] (%)	isomer ratio[b] endo : exo
	15	7.5	96	4 : 1
	15	3.0	93	19 : 3
	20	5.5	98	13 : 1
	15	15	90	5 : 1
	10	15	98	5 : 1

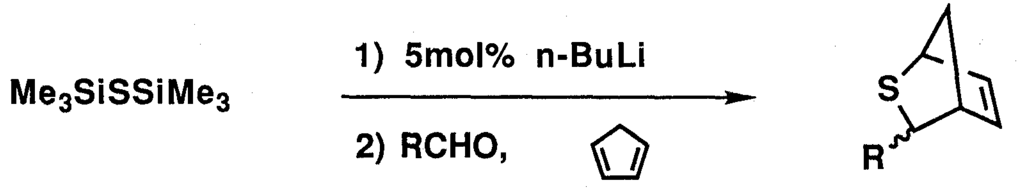
[a] Isolated yield. [b] Determined by ^{1}H-NMR.

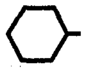
Table 3-1. (Continued)

RCHO R=	temp. (°C)	time (h)	yield[a] (%)	isomer ratio[b] endo : exo
	15	17	96	3 : 1
	15	20	79	9 : 2
	20	9.5	85	4 : 1
	10	5.0	94	3 : 1
	10	14	84	13 : 4
	10	4.5	97	5 : 1
	20	6.5	98	10 : 3
	20	4.0	83	4 : 1

[a] Isolated yield. [b] Determined by ^{1}H-NMR.

Table 3-2. Generation and Trapping of Aliphatic Thioaldehydes in the Presence of Cyclopentadiene



RCHO R=	temp. (°C)	time (h)	yield[a] (%)	isomer ratio[b] endo : exo
$PhCH_2$	55	5.0	52	3 : 1
n-Pr	55	5.0	80	6 : 1
	55	4.0	77	7 : 1
i-Pr	55	5.0	57	9 : 1
t-Bu	55	4.5	86	>20 : 1

[a] Isolated yield. [b] Determined by ^{1}H-NMR.

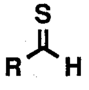
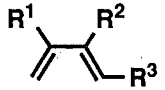
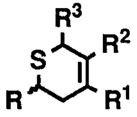
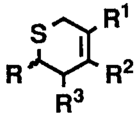
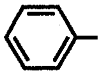
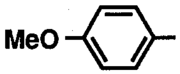
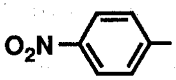
aldehydes having substituted phenyl, naphthyl, furyl, or thienyl group underwent desired conversion without affecting that substituent. Aliphatic thioaldehydes were generated at somewhat higher temperature (55 °C) compared with aromatic compounds. In all entries the good yields are obtained and imply that thioaldehyde generation occurs very efficiently under this base-catalyzed condition. The cycloadducts gave a mixture of endo and exo isomers, with the former predominating in all cases. These results are similar to those of selenoaldehyde cycloaddition with cyclopentadiene.

On the other hand, Diels-Alder reaction of aromatic thioaldehydes with an acyclic 1,3-diene proceeded also efficiently to yield the cycloadducts in good yields as a mixture of stereo- and regio-isomers. However, the success of Diels-Alder trapping depended more strongly on the choise of diene and the nature of thioaldehyde substituent R. The combination such as the treatment of aliphatic thioaldehydes and an acyclic diene did not give a satisfactory result, and the best results were obtained with cyclopentadiene (see Table 3-2). The yields and the regioisomer ratios of the adducts are summarized in Table 3-3. The isomer ratios were determined by suitable NMR resonances. None of the regio- and stereo-isomer mixture was separable by flash column chromatography. Generally, the remarkable regioselectivity in this reaction was not observed.

The reaction of **1** with cinnamaldehyde in the absence of a

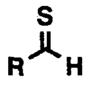
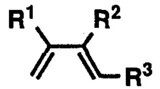
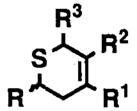
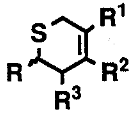
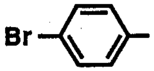
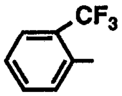
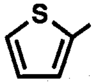
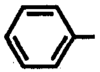
Table 3-3. Diels-Alder Reaction of Thioaldehydes with Acyclic 1,3-diene

$$(Me_3Si)_2S + RCHO \xrightarrow[\text{Diene, 40-60°C in THF}]{\text{10mol\% n-BuLi}} \text{Cycloadducts}$$

thioaldehyde	diene			product		
				yield(%)[a]	isomer ratio[b]	
 R=	 R^1=	R^2=	R^3=		 A	 B
	H	H	Me	90	37	63
	Me	H	Me	93	49	51
	H	H	Ph	79	44	56
	$OSiMe_2Bu^t$	H	H	76	66	34
	H	H	Me	84	40	60
	Me	H	Me	95	57	43
	H	H	Ph	78	46	54
	Me	H	Me	48	17	83
	H	H	Ph	59	30	70

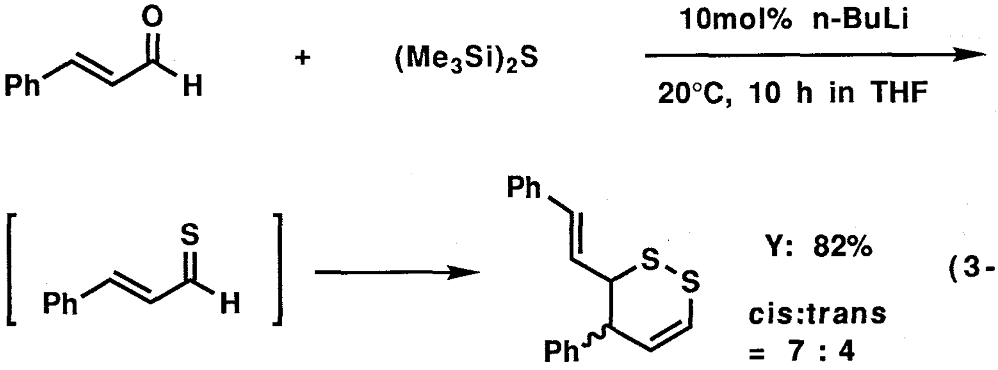
[a] Isolated yield. [b] Determined by ^1H-NMR.

Table 3-3. (Continued)

thioaldehyde	diene			product		
				yield(%)[a]	isomer ratio[b]	
 R=	 R^1=	R^2=	R^3=		 A	 B
	H	H	Me	89	39	61
	H	H	Ph	76	34	66
	H	H	Me	97	55	45
	Me	H	Me	79	49	51
	H	H	Me	95	32	68
	Me	H	Me	97	32	68
n-Pr	Me	H	Me	—	———	
				—	———	

[a]Isolated yield. [b]Determined by ^{1}H-NMR.

diene afforded the dimeric thiocinnamaldehyde adduct regioselectively in 82% yield, with head-to-head coupling of sulfur atoms as a mixture of cis and trans isomers (7 : 4), as shown in eq. 3-2. The structure of the dimer was determined by careful analyses of coupling constants (see Experimental aection) and decoupling experiments in the 400 MHz ^{1}H-NMR spectrum. It would be conceivable that a [4 + 2] cycloaddition could occur involving one thiocinnamaldehyde molecule reacting as a 4π-electron component, for the formation of the dimer.

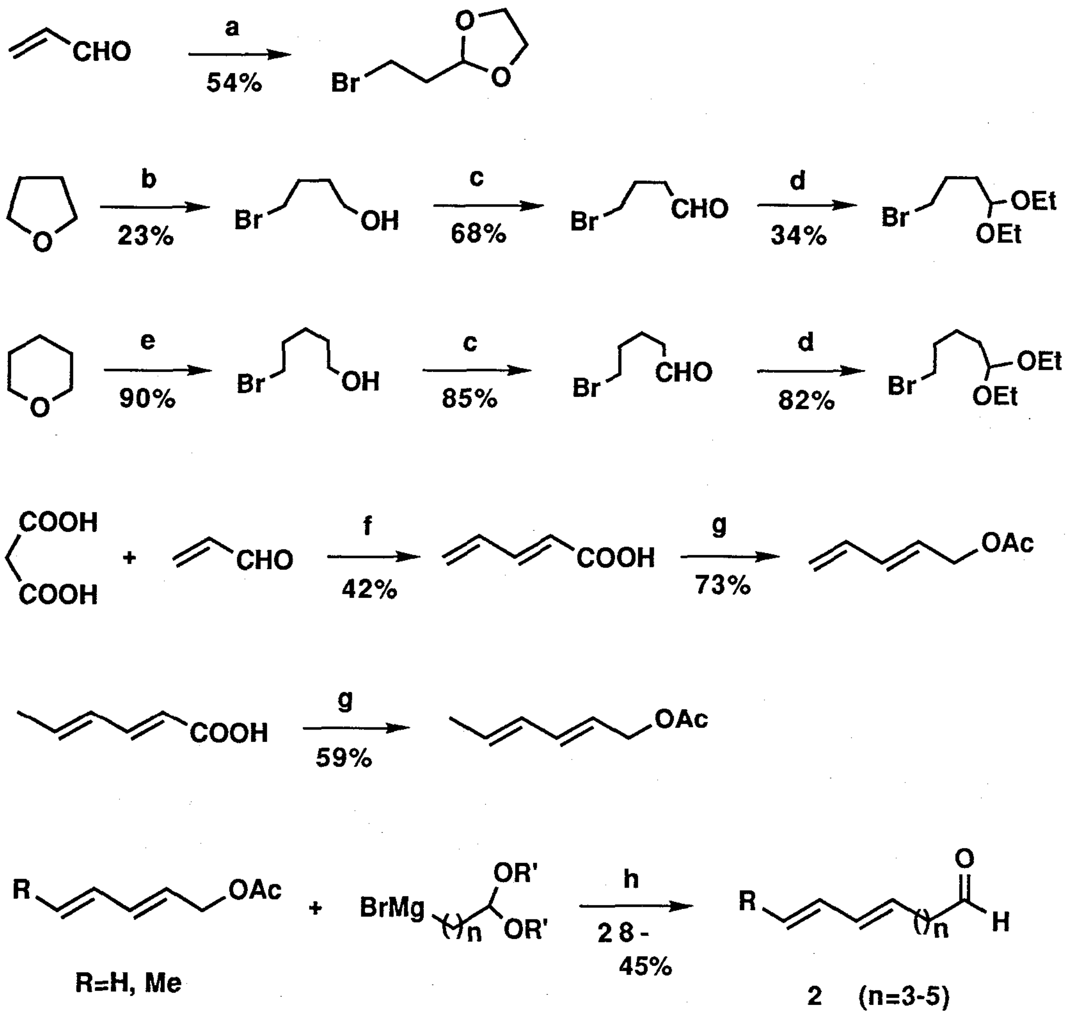


(3-2)

3-3 Intramolecular Diels-Alder Reaction of Thioaldehydes

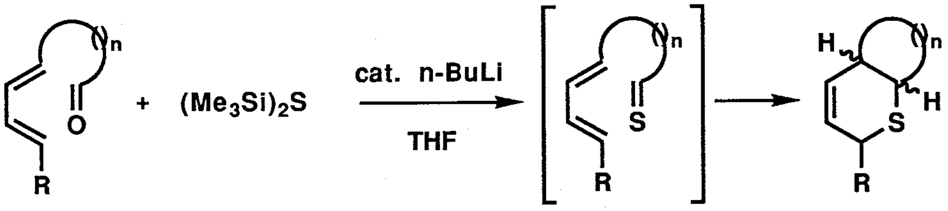
This section describes the results on the generation of dienethials from dienals by the base-catalyzed method[6] and their subsequent intramolecular Diels-Alder reaction (eq. 3-3).

The requisite dienals were prepared by the methods outlined in Scheme 3-1. Protected bromoaldehyde having three



a, HBr in HOCH$_2$CH$_2$OH b, 47% HBr aq. in THF, reflux c, PCC in CH$_2$Cl$_2$ d, cat. TsOH, HC(OEt)$_3$ in EtOH e, AcBr f, in pyridine, 70°C g, LAH in Et$_2$O, then Ac$_2$O in pyridine h, cat. Li$_2$CuCl$_4$ in THF, -15°C-r.t.

Scheme 3-1

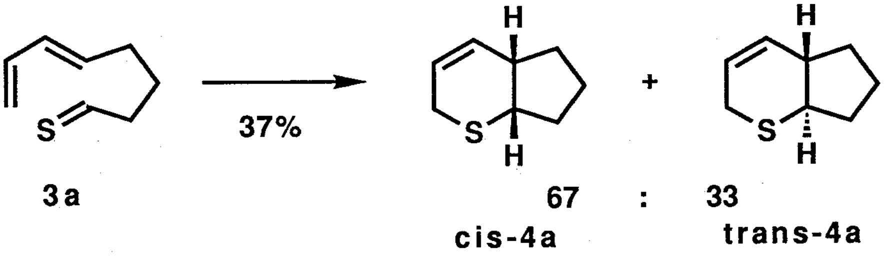


(3-3)

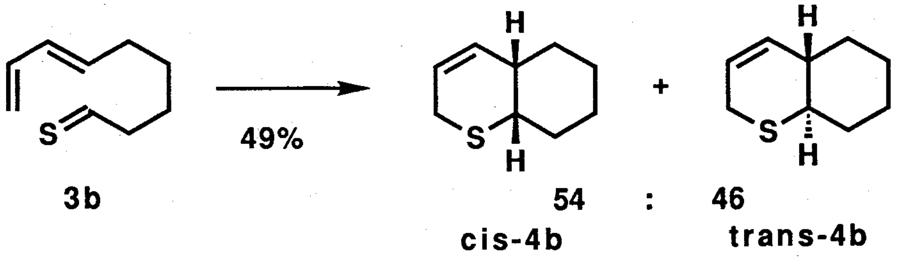
2 1 3 4

carbon chain was prepared by addition of hydrogen bromide to acrolein in ethylene glycol in 54% yield.[9] Bromoacetals were prepared by acetalization of the corresponding aldehydes derived from the ring-opening products of tetrahydrofuran and tetrahydropyran, respectively.[10] For the synthesis of trans, trans-2,4-pentadienyl acetate,[11] malonic acid was treated with acrolein in pyridine to give 2,4-pentadienoic acid in 42% yield. Reduction of 2,4-pentadienoic acid with $LiAlH_4$ followed by acetylation with acetic anhydride and pyridine gave the acetate in a 73% yield. The allylic acetate was similarly prepared from commercially available sorbic acid in 59% yield.[11] Copper-catalyzed cross-coupling of the acetate with Grignard reagent derived from protected bromoaldehyde followed by deprotection (acetic acid) gave the corresponding dienals in 28-45% yields.[12]

Thioaldehydes **3** containing dienyl units were generated from the corresponding aldehydes **2** and bis(trimethylsilyl) sulfide **1** in the presence of 10 mol% n-BuLi and underwent intramolecular Diels-Alder reaction in situ to give cycloadducts **4**. To minimize intermolecular reaction, all reactions were carried out under high-dilution conditions in THF (0.03 M solution). The internal cycloaddition of trans-5,7-octadienethial **3a** gave the bicyclic adduct as a 67 : 33 mixture of cis and trans-fused isomers in 37 % combined yield (eq. 3-4). The configuration of the isomers was assigned from the coupling constants of the bridgehead hydrogens on the 400 MHz ^{1}H-NMR spectra (cis-**4a** : 7.6 Hz, trans-**4a** : 11.9 Hz). Similarly, trans-6,8-nonadienethial **3b** underwent cycloaddition to give the bicyclic compounds **4b** in a cis/trans ratio of 54 : 46 in 49 % yield (eq. 3-5). However, trans-7,9-decadienethial **3c** with five methylene units did not afford the expected intramolecular Diels-Alder adduct **4c** having fused six- and seven-membered rings (eq. 3-6).

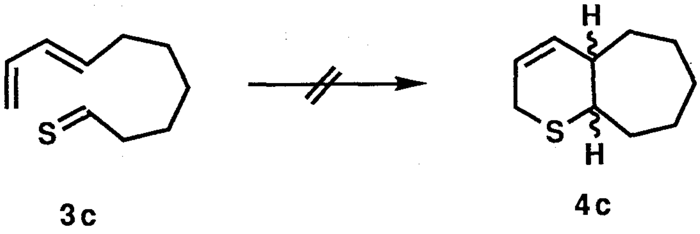


(3-4)



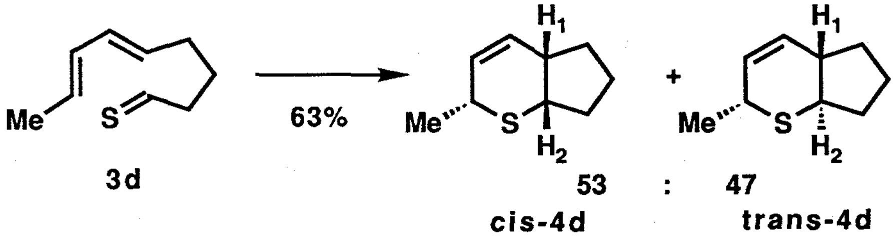
(3-5)

In the case of the reaction of **3d** or **3e** having methyl

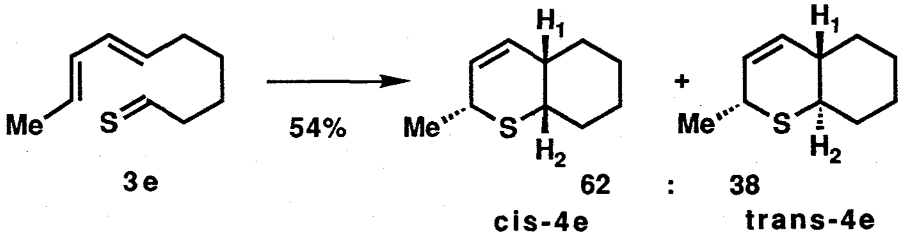


(3-6)

substituent on the terminal carbon atom of the diene, only two stereoisomers with respect to the bridgehead hydrogens (H_1 and H_2) were obtained (eqs. 3-7 and 3-8). The stereochemical relationship between the methyl group and H_1 could not be clearly determined from ^{1}H-NMR data. However, this stereochemical configuration is presumed to be trans by considering both the geometry of starting dienals (trans, trans-form) and the probable concerted [4 + 2] mechanism in the present intramolecular cycloaddition.



(3-7)



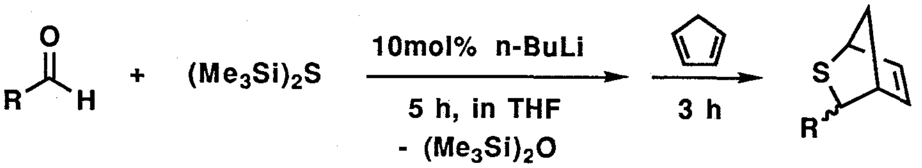
(3-8)

In all cases, stereoselectivity was not impressive but regiochemistry was completely controlled with the bond formation between the terminal carbon atom and the sulfur atom of the thiocarbonyl group. These regiochemical preferences are consistent with results in our studies of selenoaldehydes.[7]

In conclusion, the thioaldehydes connected to diene units with suitable carbon chain undergoes intramolecular cyclization to afford the corresponding bicyclic adducts. This is in contrast with the observation that thioaldehydes do not react intermolecularly with a simple diene except for electron-rich diene.[5] The cycloadducts described above would be amenable to further synthetic elaboration.

3-4 Reaction of Aldehydes with Bis(trimethylsilyl) Sulfide in the Absence of a Trapping Reagent

Thioaldehydes are generally known to polymerize to stable trimers at ambient temperature in the absence of an efficient trapping reagent. In our base-catalyzed method for thioaldehyde generation, the reaction of bis(trimethylsilyl) sulfide 1 with benzaldehyde in the absence of a diene gave no trimer of the corresponding thiobenzaldehyde. However, the complete consumption of 1 and the quantitative formation of hexamethyldisiloxane were confirmed by ^{1}H-NMR measurement after 3 h at room temperature. These results imply strongly in situ generation of thiobenzaldehyde under this condition. The reaction of 1 with benzaldehyde in the absence of a diene for 5 h followed by addition of excess amounts of cyclopentadiene yielded the Diels-Alder cycloadduct of the correspondig thiobenzaldehyde and cyclopentadiene in 90% yield after 3 h as shown in eq. 3-9.



(3-9)

R	temp.(°C)	yield(%)[a]
Ph	25	90
t-Bu	65	81

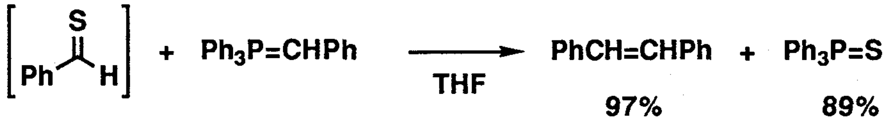
[a]Isolated yield.

Similarly, the use of pivalaldehyde as a starting aldehyde gave the thiopivalaldehyde cycloadduct with cyclopentadiene in 81% yield. The formation of cycloadducts suggests that an aldehyde is converted into a precursor of thioaldehyde by the reaction with 1 in the absence of a trapping reagent under the base condition. To determine the structure of the precursor in the case of benzaldehyde, the removal of low-boiling volatiles carefully from the reaction mixture followed by the measurement of molecular weight of the residue were performed. The molecular weight of that compound was estimated to be about 1000-1500. Furthermore, ^{1}H-NMR spectrum of the precursor revealed one methine proton as a broad signal at δ 4.3. On the other hand, addition of trimethylsilyl chloride to the reaction mixture at the stage of the precursor formation no longer led to the generation of thioaldehyde even in the presence of cyclopentadiene. From these experimental proofs it may be presumed that the precursor is a linear living-polymer of thioaldehyde. Thus, for thioaldehyde formation a catalytic cycle depicted in Scheme 3-2 is proposed in analogy with the mechanism of selenoaldehyde generation.

3-5 Wittig Type Reaction of Thioaldehydes

In previous section, formation of a thioaldehyde precursor, which may enable to study the reactivity of thioaldehydes, was mentioned. This section describes the investigation of Wittig type reaction with a phosphonium ylide and the other reactions.

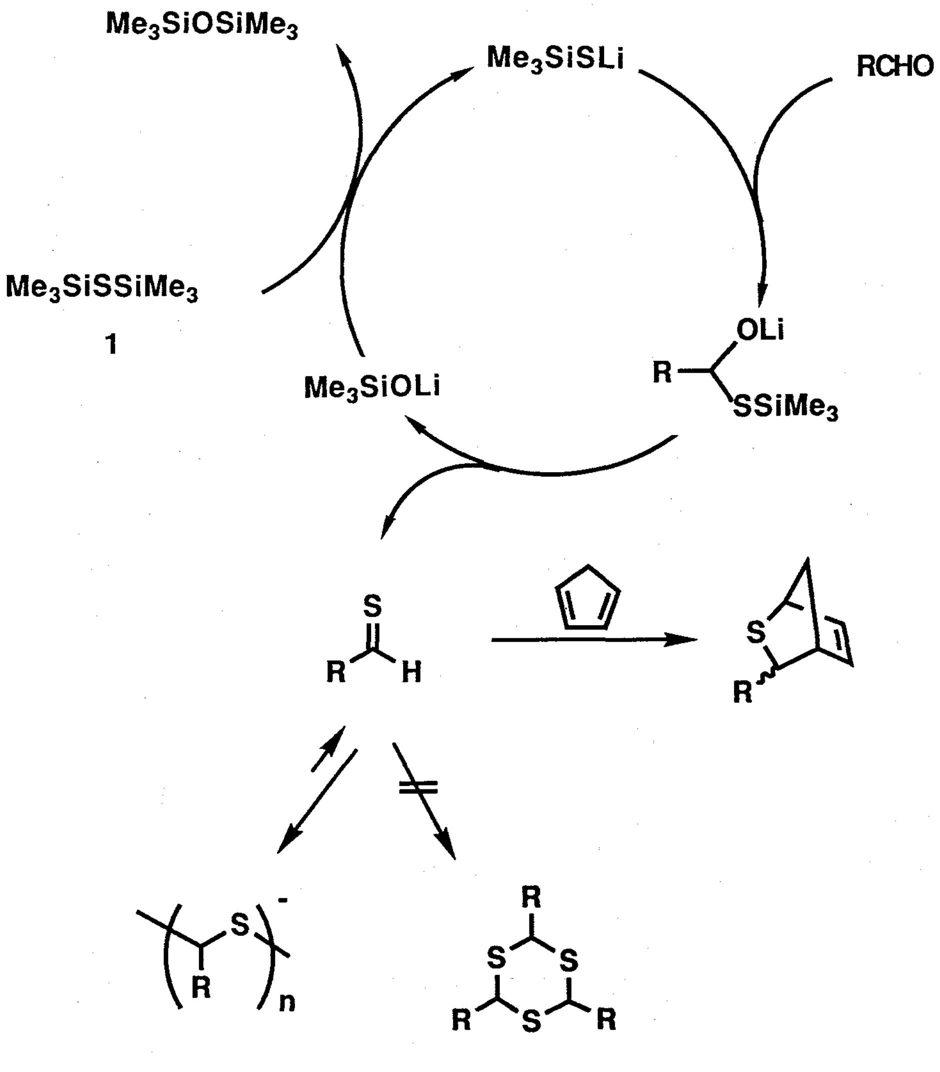
The reaction of the thiobenzaldehyde precursor with benzylidenetriphenylphosphorane gave stilbene and triphenylphosphine sulfide in 97 and 89% yields, respectively (eq. 3-10).



(3-10)

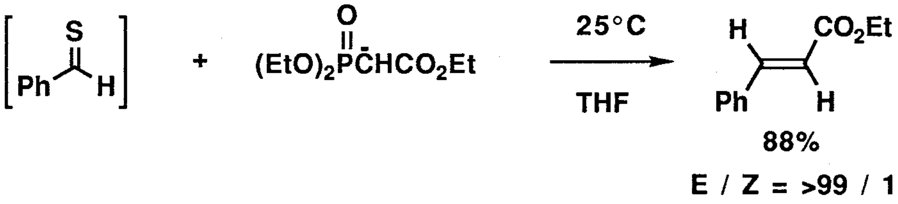
Stilbene obtained in this reaction was a 88 : 12 mixture of trans and cis isomers. In this connection, the Wittig reaction of benzaldehyde with that ylide gave stilbene as a 45 : 55 mixture of trans and cis isomers in 90% yield under the same

$$\mathrm{Me_3SiSSiMe_3} \quad + \quad \text{n-BuLi} \longrightarrow \mathrm{Me_3SiSLi} \quad + \quad \text{n-BuSiMe}_3$$



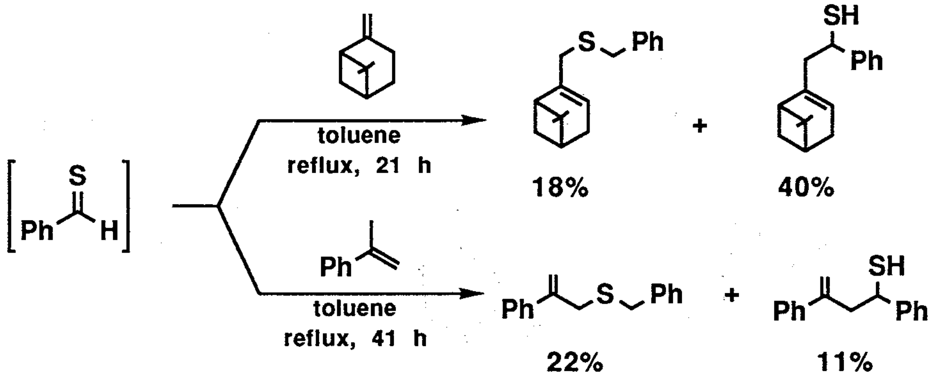
Scheme 3-2

reaction condition. Further examples of the reaction of the thioaldehyde precursor with a phosphonium ylide are summarized in Table 3-4. These results suggest that in situ generation of thioaldehyde occurs efficiently under this condition. Similarly, the Wittig-Horner type reaction with the carbanion of triethylphosphonoacetate furnished only ethyl trans-cinnamate in 88% yield (eq. 3-11).



(3-11)

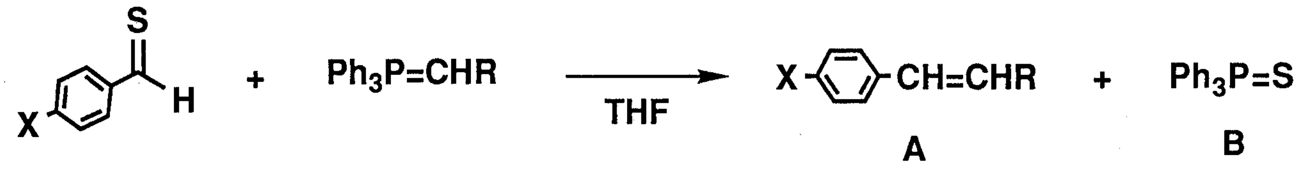
Next, the ene-type reaction of the thiobenzaldehyde precursor with β-pinene in refluxing toluene proceeded to give the corresponding thiol and sulfide in moderate yields (eq. 3-12). These results were consistent with those reported by



(3-12)

Baldwin and Lopez.[6a] Further, when the reaction with a primary

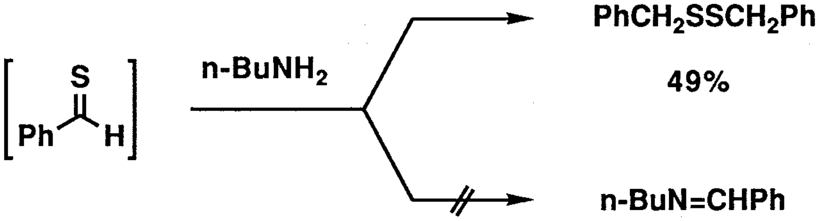
Table 3-4. Wittig Reaction of Aromatic Thioaldehydes with a Phosphonium ylide



thioaldehyde X=	ylide R=	temp. (°C)	yield(%)		isomer ratio[a]
			A	B	E : Z
H	Ph	25	97	89	88 : 12
H	CO_2Me	66	82	95	>99 : 1
H	CO_2Et	66	76	90	>99 : 1
Me	Ph	25	89	90	93 : 7
Me	CO_2Et	66	89	86	>99 : 1
OMe	Ph	40	92	85	——

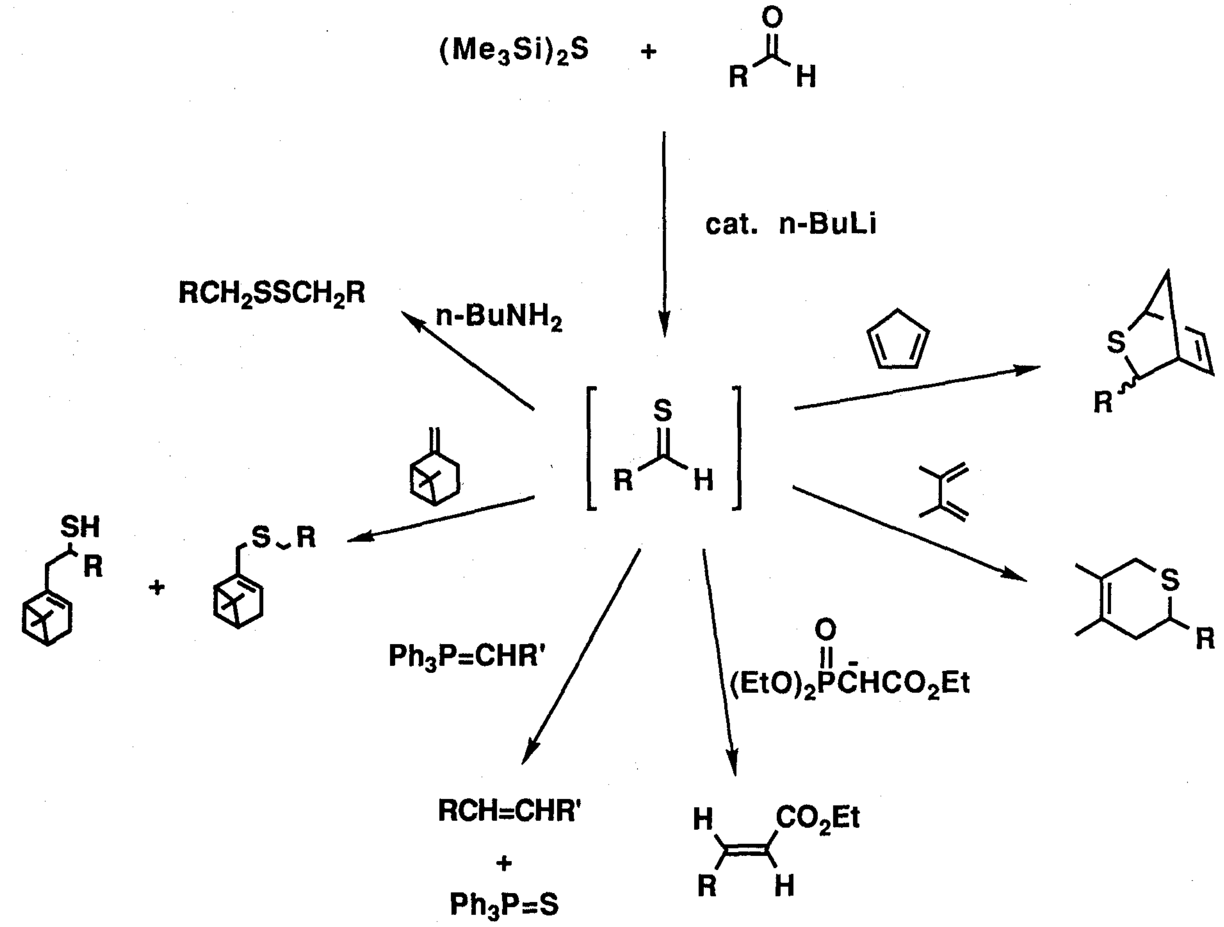
[a] Determined by ^{1}H-NMR.

amine such as n-butylamine was conducted, dibenzyl disulfide was obtained in 49% yield as shown in eq. 3-13. In this reaction, no imine which are a normal product in the reaction of aldehyde with a primary amine was detected.



(3-13)

Finally, some reactions of thioaldehyde generated by our base-catalyzed method are summarized in Scheme 3-3.


(Me$_3$Si)$_2$S
+
O
R
H
cat. n-BuLi
S
R
H
n-BuNH$_2$
RCH$_2$SSCH$_2$R
SH
R
+
S
R
Ph$_3$P=CHR'
RCH=CHR'
+
Ph$_3$P=S
O
(EtO)$_2$P̄CHCO$_2$Et
H
CO$_2$Et
R
H
S
R
S
R

Scheme 3-3

3-6 Experimental

Apparatus

Melting points were recorded on a Yanagimoto MP-S2 melting point apparatus. Melting points are uncorrected. ^{1}H-NMR spectra were determined on a JEOL JNM-GX-400 spectrometer at 399.65 MHz and are reported in parts per million (δ) downfield from internal tetramethylsilane (TMS) in $CDCl_3$. Data are reported as follows: chemical shift, multiplicity (s=singlet, d=doublet, t=triplet, q=quartet, m=multiplet, br=broad) coupling constant (Hz), integration, and interpretation. Infrared spectra were obtained on a JASCO A-202 spectrometer and absorptions are reported in reciprocal centimeters. Mass spectra were recorded on a Hitachi M-80 spectrometer. Elemental analyses were performed on a Yanagimoto CHN-Corder MT-2 and MT-3.

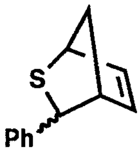
Materials

Tetrahydrofuran (THF) was freshly distilled from potassium /benzophenone just prior to use. Super Hydride®, butyllithium, and chloroform-d were purchased from Aldrich Chemicals, Ltd. and without purification. Elemental sulfur (99.999%) was purchased from Nakarai Chemicals, Ltd. Chlorotrimethylsilane was distilled from calcium hydride. Cyclopentadiene was obtained by heating (160-180 °C) technical dicyclopentadiene carefully under a fractionating colum. The other dienes, aldehydes, and other compounds were purchased from commercial sources and purified by distillation. Bis(trimethylsilyl) sulfide[8] and phosphonium halides[13] were prepared according to the reported procedures.

<u>General Procedure for the Generation and Trapping of Thioaldehyde Using Bis(trimethylsilyl) Sulfide</u>

A typical experimental procedure is exemplified by the synthesis of thiobenzaldehyde cycloadduct. Butyllithium (1.6 M solution in hexane, 0.032 mL, 0.05 mmol) was added to a solution of bis(trimethylsilyl) sulfide (178 mg, 1.0 mmol) in THF (30 mL) at 0 °C under nitrogen. After stirring for 30 min at 0 °C, cyclopentadiene (330 mg, 5.0 mmol) and benzaldehyde (159 mg, 1.5 mmol) were added in that order. The reaction mixture was stirred at 15 °C for 7.5 h. Evaporation of the solvent followed by a flash column chromatography on silica gel (hexane:dichloromethane=2:1 as eluent) yielded the thiobenzaldehyde cycloadduct (180 mg, 96% yield) as a 4 : 1 mixture of endo and exo isomers.

3-Phenyl-2-thiabicyclo[2.2.1]hept-5-ene (endo:exo=4:1)



^{1}H-NMR endo δ 7.16-7.33(m, 5H, ArH), 6.50(dd. J_1=3.1Hz, J_2=5.5 Hz, 1H, C-6), 5.51(dd, J_1=3.1Hz, J_2=5.5Hz, 1H, C-5), 4.92(d, J=4.0Hz, 1H, C-3), 4.13(br s, 1H, C-1), 3.55(br s, 1H, C-4), 1.81(d, J=8.9Hz, 1H, C-7), 1.75(dt, J_1=8.9 Hz, J_2=2.1Hz, 1H, C-7).

exo δ 7.17-7.34(m, 5H, ArH), 6.40(dd, J_1=2.8Hz, J_2=5.5 Hz, 1H, C-6), 6.12(dd, J_1=3.1Hz, J_2=5.5Hz, 1H, C-5), 4.21 (br s, 1H, C-1), 4.02(s, 1H, C-3), 3.25(br s, 1H, C-4), 1.88(d, J=9.5Hz. 1H, C-7), 1.61(dt, J_1=9.5Hz, J_2= 2.1Hz, 1H, C-7).

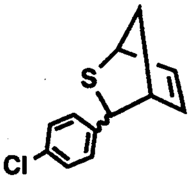
IR (NaCl, neat) 3055, 2930, 1594, 1492, 1442, 1339, 733, 695 cm^{-1},

MS, m/e(relative intensity) 188(M$^+$, 29), 155(26), 123(55), 122 (90), 121(58), 77(19), 66(100).

Anal. Calcd for $C_{12}H_{12}S$: C, 76,55; H, 6.42.

Found: C, 76.46; H, 6.41.

3-(4-Chlorophenyl)-2-thiabicyclo[2.2.1]hept-5-ene (endo:exo=5:1)



^{1}H-NMR <u>endo</u> δ 7.16-7.22(m, 4H, ArH), 6.50(dd. J_1=3.1Hz, J_2=5.5 Hz, 1H, C-6), 5,48(dd, J_1=3.1Hz, J_2=5.5Hz, 1H, C-5), 4.87(d, J=4.0Hz, 1H, C-3), 4.14(br s, 1H, C-1), 3.51(br s, 1H, C-4), 1.80(br d, J=9.2Hz, 1H, C-7), 1.75(dt, J_1= 9.2Hz, J_2=2.1Hz, 1H, C-7).

<u>exo</u> δ 7.45(br d, J=8.2Hz, 2H, ArH), 7.29(br d, J=8.2Hz, 2H, ArH), 6.40(dd, J_1=2.7Hz, J_2=5.5Hz, 1H, C-6), 6.11 (dd, J_1=3.4Hz, J_2=5.5Hz, 1H, C-5), 4.21(br s, 1H, C-1), 3.96(s, 1H, C-3), 3.20(br s, 1H, C-4), 1.80(br d, J=9.2 Hz, 1H, C-7), 1.60(dt, J_1=9.2Hz, J_2=2.1Hz, 1H, C-7).

IR (NaCl, neat) 2950, 1490, 1090, 1010 cm^{-1}.

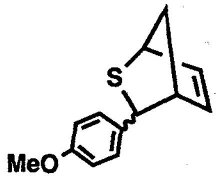
MS, m/e(relative intensity) 223(M^+, 27), 159(17), 157(62), 156 (77), 155(48), 66(100).

Anal. Calcd for $C_{12}H_{11}ClS$: C, 64.71; H, 4.98.

Found: C, 64.68; H, 4.97.

3-(4-Methoxyphenyl)-2-thiabicyclo[2.2.1]hept-5-ene

(endo:exo=3:1)



^{1}H-NMR <u>endo</u> δ 7.16(d, J=8.9Hz, 2H, ArH), 6.78(d, J=8.9Hz, 2H, ArH), 6.50(dd, J_1=2.7Hz, J_2=5.5Hz, 1H, C-6), 5.53(dd, J_1 =2.7Hz, J_2=5.5Hz, 1H, C-5), 4.88(d, J=3.7Hz, 1H, C-3), 4.11(br s, 1H, C-1), 3.77(s, 3H, OMe), 3.51(br s, 1H, C-4), 1.79(br d, J=9.2Hz, 1H, C-7), 1.74(dt, J_1=9.2Hz, J_2=2.4Hz, 1H, C-7).

exo δ 7.42(d, J=8.9Hz, 2H, ArH), 6.87(d, J=8.9Hz, 2H, ArH), 6.39(dd, J_1=2.7Hz, J_2=5.5Hz, 1H, C-6), 6.11(dd, J_1 =3.1Hz, J_2=5.5Hz, 1H, C-5), 4.20(br s, 1H, C-1), 3.98(s, 1H, C-3), 3.80(s, 3H, OMe), 3.20(br s, 1H, C-4), 1.86(br d, J=9.2Hz, 1H, C-7), 1.61(dt, J_1=9.2Hz, J_2=2.4Hz, 1H, C-7).

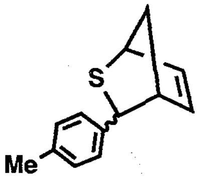
IR (NaCl, neat) 2950, 2834, 1610, 1515, 1250, 1180, 1032 cm^{-1}.

MS, m/e(relative intensity) 218(M^+, 10), 152(100), 151(58), 66(20).

Anal. Calcd for $C_{13}H_{14}OS$: C, 71.52; H, 6.46.

Found: C, 71.54; H, 6.47.

3-(4-Methylphenyl)-2-thiabicyclo[2.2.1]hept-5-ene (endo:exo=4:1)



^{1}H-NMR endo δ 7.13(d, J=8.2Hz, 2H, ArH), 7.04(d, J=8.2Hz, 2H, ArH), 6.50(dd, J_1=2.7Hz, J_2=5.5Hz, 1H, C-6), 5.53(dd, J_1 =3.0Hz, J_2=5.5Hz, 1H, C-5), 4.89(d, J=4.0Hz, 1H, C-3), 4.12(br s, 1H, C-1), 3.53(br s, 1H, C-4), 2.30(s, 3H, Me), 1.79(br d, J=9.2Hz, 1H, C-7), 1.74(dt, J_1=9.2Hz, J_2 =2.1Hz, 1H, C-7).

<u>exo</u> δ 7.39(d, J=8.2Hz, 2H, ArH), 7.15(d, J=8.2Hz, 2H, ArH), 6.39(dd, J_1=2.7Hz, J_2=5.5Hz, 1H, C-6), 6.11(dd, J_1=3.4Hz, J_2=5.5Hz, 1H, C-5), 4.20(br s, 1H, C-1), 3.99(s, 1H, C-3), 3.22(br s, 1H, C-4), 2.34(s, 3H, Me), 1.87(br d, J=9.5Hz, 1H, C-7), 1.69(dt, J_1=9.5Hz, J_2=2.1Hz, 1H, C-7).

IR (NaCl, neat) 3050, 2955, 2900, 1510, 1442 cm^{-1}.

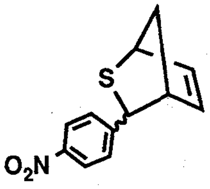
MS, m/e(relative intensity) 202(M^+, 16), 137(31), 136(100), 135(69), 91(26), 66(35), 39(13).

Anal. Calcd for $C_{13}H_{14}S$: C, 77.18; H, 6.97.

Found: C, 77.18; H, 6.92.

3-(4-Nitrophenyl)-2-thiabicyclo[2.2.1]hept-5-ene

(endo:exo=9:2)



^{1}H-NMR <u>endo</u> δ 8.09(d, J=8.9Hz, 2H, ArH), 7.42(d, J=8.9Hz, 2H, ArH), 6.55(dd, J_1=3.1Hz, J_2=5.5Hz, 1H, C-6), 5.44(dd, J_1=3.1Hz, J_2=5.5Hz, 1H, C-5), 4.97(d, J=4.0Hz, 1H, C-3), 4.21(br s, 1H, C-1), 3.59(br s, 1H, C-4), 1.85(br d, J=9.2Hz, 1H, C-7), 1.80(dt, J_1=9.2Hz, J_2=2.1Hz, 1H, C-7).

<u>exo</u> δ 8.19(d, J=8.9Hz, 2H, ArH), 7.69(d, J=8.9Hz, 2H, ArH), 6.45(dd, J_1=2.8Hz, J_2=5.5Hz, 1H, C-6), 6.15(dd, J_1=3.4Hz, J_2=5.5Hz, 1H, C-5), 4.28(br s, 1H, C-1), 4.05(s,

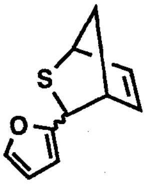
1H, C-3), 3.28(br s, 1H, C-4), 1.85(br d, J=9.2Hz, 1H, C-7), 1.64(dt, J_1=9.2Hz, J_2=2.1Hz, 1H, C-7).

IR (NaCl, neat) 3000, 2950, 2850, 1600, 1520, 1360, 1250, 1090 cm^{-1}.

MS, m/e(relative intensity) 233(M^+, 17), 167(33), 121(10), 77 (11), 66(100).

Anal. Calcd for $C_{12}H_{11}NO_2S$: C, 61.78; H, 4.75; N, 6.00.
Found: C, 61.72; H, 4.74; N, 6.12.

3-(2-Furyl)-2-thiabicyclo[2.2.1]hept-5-ene (endo:exo=3:1)



^{1}H-NMR endo δ 7.30(dd, J_1=0.9Hz, J_2=1.8Hz, 1H, FurylH), 6.47 (dd, J_1=2.7Hz, J_2=5.5Hz, 1H, C-6), 6.22(dd, J_1=1.8Hz, J_2 =3.4Hz, 1H, FurylH), 6.00(dt, J_1=3.4Hz, J_2=0.9Hz, 1H, FurylH), 5.64(dd, J_1=3.1Hz, J_2=5.5Hz, 1H, C-5), 4.86(d, J=3.7Hz, 1H, C-3), 4.11(br s, 1H, C-1), 3.69(br s, 1H, C-4), 1.76(dt, J_1=9.2Hz, J_2=2.1Hz, 1H, C-7), 1.73(br d, J=9.2Hz, 1H, C-7).

exo δ 7.37(dd, J_1=0.9Hz, J_2=1.8Hz, 1H, FurylH), 6.40(dd, J_1=2.7Hz, J_2=5.5Hz, 1H, C-6), 6.31(dd, J_1=1.8Hz, J_2=3.4 Hz, 1H, FurylH), 6.25(dt, J_1=3.4Hz, J_2=0.9Hz, 1H, FurylH), 6.04(dd, J_1=3.1Hz, J_2=5.5Hz, 1H, C-5), 4.17(br s, 1H, C-1), 3.93(s, 1H, C-3), 3.43(br s, 1H, C-4), 1.91(br d, J=9.5Hz, 1H, C-7), 1.68(dt, J_1=9.5Hz, J_2=2.1Hz, 1H, C-7).

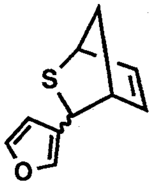
IR (NaCl, neat) 3000, 1500, 1440, 1340, 740 cm^{-1}.

MS, m/e(relative intensity) 178(M^+, 34), 115(14), 112(100), 111 (14), 84(21), 66(69), 39(17).

Anal. Calcd for $C_{10}H_{10}OS$: C, 67.38; H, 5.65.

Found: C, 67.21; H, 5.69.

3-(3-Furyl)-2-thiabicyclo[2.2.1]hept-5-ene (endo:exo=13:4)



^{1}H-NMR <u>endo</u> δ 7.30(t, J=1.8Hz, 1H, FurylH), 7.21(m, 1H, FurylH) 6.47(dd, J_1=3.1Hz, J_2=5.5Hz, 1H, C-6), 6.25(m, 1H, Furyl H), 5.65(dd, J_1=3.1Hz, J_2=5.5Hz, 1H, C-5), 4.75(d, J=3.7Hz, 1H, C-3), 4.08(br s, 1H, C-1), 3.52(br s, 1H, C-4), 1.75(dt, J_1=9.2Hz, J_2=2.1Hz, 1H, C-7), 1.72(br d, J=9.2Hz, 1H, C-7).

<u>exo</u> δ 7.44(m, 1H, FurylH), 7.39(t, J=1.8Hz, 1H, FurylH), 6.42(m, 1H, FurylH), 6.37(dd, J_1=2.8Hz, J_2=5.5Hz, 1H, C-6), 6.04(dd, J_1=3.4Hz. J_2=5.5Hz, 1H, C-5), 4.14(br s, 1H, C-1), 3.80(s, 1H, C-3), 3.23(br s, 1H, C-4), 1.72(br d, J=9.2Hz, 1H, C-7), 1.65(dt, J_1=9.2Hz, J_2=2.1Hz, 1H, C-7).

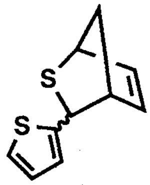
IR (NaCl, neat) 3125, 2950, 2925, 1500, 1440, 1340, 860, 740 cm^{-1}.

MS, m/e(relative intensity) 178(M$^+$, 39), 115(11), 112(60), 111 (36), 66(100), 39(19).

Anal. Calcd for $C_{10}H_{10}OS$: C, 67.38; H, 5.65.

Found: C, 66.38; H, 5.53.

3-(2-Thienyl)-2-thiabicyclo[2.2.1]hept-5-ene (endo:exo=5:1)



^{1}H-NMR endo δ 7.10-7.11(m, 1H, ThienylH), 6.90-6.91(m, 1H, ThienylH), 6.86-6.88(m, 1H, ThienylH), 6.56(dd, J_1=3.1 Hz, J_2=5.5Hz, 1H, C-6), 5.69(dd, J_1=3.4Hz, J_2=5.5Hz, 1H, C-5), 5.15(d, J=3.7Hz, 1H, C-3), 4.12(br s, 1H, C-1), 3.59(br s, 1H, C-4), 1.78(t, J=1.8Hz, 2H, C-7).

exo δ 7.18-7.19(m, 1H, ThienylH), 7.05-7.07(m, 1H, ThienylH), 6.94-6.96(m, 1H, ThienylH), 6.39(dd, J_1=2.7 Hz, J_2=5.5Hz, 1H, C-6), 6.08(dd, J_1=3.4Hz, J_2=5.5Hz, 1H, C-5), 4.19(s, 1H, C-3), 3.30(br s, 1H, C-4), 1.97(d, J= 9.5Hz, 1H, C-7), 1.70(dt, J_1=9.5Hz, J_2=2.1Hz, 1H, C-7).

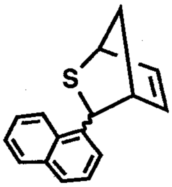
IR (NaCl, neat) 3055, 2930, 1608, 1423, 1400, 1325, 1240, 762, 734 cm^{-1}.

MS, m/e(relative intensity) 194(M$^+$, 38), 129(49), 128(100), 127 (41), 66(34).

Anal. Calcd for $C_{10}H_{10}S_2$: C, 61.81; H, 5.19.

Found: C, 61.75; H, 5.13.

3-Naphtyl-2-thiabicyclo[2.2.1]hept-5-ene (endo:exo=4:1)



^{1}H-NMR endo δ 7.46-7.59(m, 7H, ArH), 6.50(dd, J_1=3.4Hz, J_2=5.5 Hz, 1H, C-6), 5.76(d, J=3.7Hz, 1H, C-3), 5.31(dd, J_1=3.4 Hz, J_2=5.5Hz, 1H, C-5), 4.19(br s, 1H, C-1), 3.79(br s, H, C-4), 1.97(br d, J=8.9Hz, 1H, C-7), 1.83(dt, J_1=8.9 Hz, J_2=2.1Hz, 1H, C-7).

exo δ 7.46-7.58(m, 7H, ArH), 6.49(dd, J_1=3.1Hz, J_2=5.5 Hz, 1H, C-6), 6.23(dd, J_1=3.1Hz, J_2=5.5Hz, 1H, C-5), 4.67(s, 1H, C-3), 4.22(br s, 1H, C-1), 3.50(br s, 1H, C-4), 1.93(br d, J=9.2Hz, 1H, C-7), 1.75(dt, J_1=9.2Hz, J_2=2.1Hz, 1H, C-7).

IR (NaCl, neat) 3050, 2970, 2920, 1600, 1510, 1440 cm^{-1}.

MS, m/e(relative intensity) 238(M^+, 17), 173(14), 172(77), 171 (100), 66(11).

Anal. Calcd for $C_{16}H_{14}S$: C, 80.63; H, 5.92.

Found: C, 80.41; H, 6.21.

3-Propyl-2-thiabicyclo[2.2.1]hept-5-ene (endo:exo=6:1)

^{1}H-NMR endo δ 6.39(dd, J_1=2.8Hz. J_2=5.5Hz, 1H, C-6), 5.75(dd, J_1=3.1Hz, J_2=5.5Hz, 1H, C-5), 3.94(br s, 1H, C-1), 3.73 (ddd, J_1=3.7Hz, J_2=5.5Hz, J_3=9.2Hz, 1H, C-3), 3.34(br s, 1H, C-4), 1.66(dt, J_1=8.9Hz, J_2=2.4Hz, 1H, C-7), 1.57(d, J=8.9Hz, 1H, C-7), 1.35-1.40(m, 2H, C-8), 1.16-1.25(m, 2H, C-9), 0.90(t, J=7.3Hz, 3H, C-10).

exo δ 6.27(dd, J_1=2.8Hz, J_2=5.5Hz, 1H, C-6), 5.93(dd, J_1 =3.4Hz, J_2=5.5Hz, 1H, C-5), 3.99(br s, 1H, C-1), 3.02(br s, 1H, C-4), 2.79(dd, J_1=5.7Hz, J_2=9.3Hz, 1H, C-3), 1.67 -1.79(m, 2H, C-8), 1.39-1.55(m, 2H, C-9), 0.95(t, J=7.3 Hz, 3H, C-10).

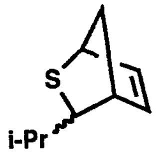
IR (NaCl, neat) 2928, 2845, 1458, 1317, 1262, 1095, 974, 783, 729 cm^{-1}.

MS, m/e(relative intensity) 154(M^+, 22), 79(16), 66(100), 55 (24), 32(22), 28(35).

Anal. Calcd for $C_9H_{14}S$: C, 70.07; H, 9.15.

Found: C, 69.89; H, 9.23.

3-Isopropyl-2-thiabicyclo[2.2.1]hept-5-ene (endo:exo=9:1)



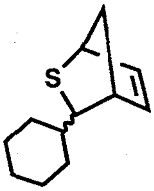
^{1}H-NMR endo δ 6.39(dd, J_1=2.8Hz, J_2=5.5Hz, 1H, C-6), 5.77(dd, J_1=3.1Hz, J_2=5.5Hz, 1H, C-5), 3.93(br s, 1H, C-1), 3.43 (br s, 1H, C-4), 3.39(dd, $J_1$3.7Hz, J_2=10.4Hz, 1H, C-3), 1.63(dt, J_1=8.9Hz, J_2=2.4Hz, 1H, C-7), 1.58(br d, J=8.9 Hz, 1H, C-7), 1.09-1.21(m, 1H, C-8), 1.06(d, J=6.4Hz, 3H, C-9), 0.93(d, J=6.4Hz, 3H, C-10).

<u>exo</u> δ 6.28(dd, J_1=2.7Hz, J_2=5.5Hz, 1H, C-6), 5.94(dd, J_1 =3.4Hz, J=5.5Hz, 1H, C-5), 3.97(br s, 1H, C-1), 3.19(br s, 1H, C-4), 2.49(d, J=9.8Hz, 1H, C-3), 1.60-1.80(m, 2H, C-7), 0.90-1.22(m, 1H, C-8), 1.10(d, J=6.4Hz, 3H, C-9), 1.09(d, J=6.4Hz, 3H, C-10).

IR (NaCl, neat) 2950, 1470, 1340, 1170, 1120 cm^{-1}.

MS, m/e(relative intensity) 154(M^+, 15), 135(16), 79(17), 71 (16), 66(100), 57(23), 55(26), 41(19), 28(55).

3-Cyclohexyl-2-thiabicyclo[2.2.1]hept-5-ene (endo:exo=7:1)



^{1}H-NMR <u>endo</u> δ 6.37(dd, J_1=2.8Hz, J_2=5.5Hz, 1H, C-6), 5.75(dd, J_1=3.1Hz, J_2=5.5Hz, 1H, C-5), 3.93(br s, 1H, C-1), 3.47 (br s, 1H, C-4), 3.44(dd, J_1=3.7Hz, J_2=10.4Hz, 1H, C-3), 1.92(br d, J=8.9Hz, 1H, C-7), 1.67(dt, J_1=8.9Hz, J_2=2.4 Hz, 1H, C-7), 1.50-1.90(m, 5H, CyclohexylH), 1.00-1.30 (m, 4H, CyclohexylH), 0.80-1.00(m, 2H, CyclohexylH).

<u>exo</u> δ 6.27(dd, J_1=2.7Hz, J_2=5.5Hz, 1H, C-6), 5.91(dd, J_1 =3.4Hz, J_2=5.5Hz, 1H, C-5), 3.96(br s, 1H, C-1), 3.25(br s, 1H, C-4), 2.53(d, J=9.8Hz, 1H, C-3), 2.10(br d,

J=11.5Hz, 1H, C-7), 1.59-1.64(m, 1H, C-7), 0.78-1.94(m, 11H, CyclohexylH).

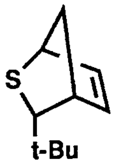
IR (NaCl, neat) 2950, 1640, 1450, 1380 cm^{-1}.

MS, m/e(relative intensity) 194(M^+, 100), 168(46), 129(85), 128 (60), 112(22), 101(34), 95(72), 83(53), 66(24), 43(17).

Anal. Calcd for $C_{12}H_{18}S$: C, 74.16; H, 9.34.

Found: C, 73.65; H, 9.42.

endo-3-tert-Butyl-2-thiabicyclo[2.2.1]hept-5-ene



^{1}H-NMR δ 6.30(dd, J_1=3.1Hz, J_2=5.5Hz, 1H, C-6), 5.76(dd, J_1=3.1 Hz, J_2=5.5Hz, 1H, C-5), 3.87(br s, 1H, C-1), 3.75(d, J= 3.4Hz, 1H, C-3), 3.42(br s, 1H, C-4), 1.61(t, J=1.8Hz, 2H, C-7), 0.91(s, 9H, C-9).

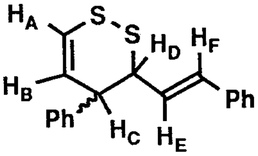
IR (NaCl, neat) 2937, 1472, 1457, 1386, 1355, 1254, 861, 756, 728 cm^{-1}.

MS, m/e(relative intensity) 168(M^+, 25), 135(15), 79(24), 69 (21), 66(100), 32(80), 28(100).

Anal. Calcd for $C_{10}H_{16}S$: C, 71.37; H, 9.58.

Found: C, 71.09; H, 9.78.

Dimer of thiocinnamaldehyde



^{1}H-NMR major isomer δ 7.18-7.40(m, 10H, ArH), 6.60(dd, 1H, H_A), 6.52(br d, 1H, H_F), 6.11(dd, 1H, H_B), 5.84(dd, 1H, H_E), 4.06(ddd, 1H, H_D), 3.93(ddd, 1H, H_C).

Coupling Constants: J_{AB}=10.37Hz, J_{AC}=1.83Hz, J_{BC}=4.27Hz, J_{CD}=4.27Hz, J_{DE}=9.46Hz, J_{EF}=15.87Hz, J_{DF}=0.61Hz.

minor isomer δ 7.18-7.40(m, 10H, ArH), 6.62(dd, 1H, H_A), 6.53(br d, 1H, H_F), 6.28(dd, 1H, H_E), 6.09(dd, 1H, H_B), 3.83(ddd, 1H, H_D), 3.76(ddd, 1H, H_C).

Coupling Constants: J_{AB}=10.37Hz, J_{AC}=1.83Hz, J_{BC}=4.02Hz, J_{CD}=6.11Hz, J_{DE}=7.63Hz, J_{EF}=15.87Hz, J_{DF}=0.90Hz.

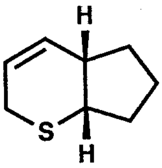
IR (NaCl, neat) 3025, 1600, 1490, 1450, 1340 cm^{-1}.

MS, m/e(relative intensity) 296(M^+, 11), 263(55), 185(17), 179 (23), 148(97), 147(100), 115(65), 103(20), 91(21), 77 (20), 45(16).

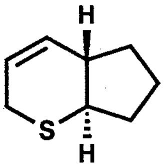
General Procedure for Intramolecular Diels-Alder Reaction of Thioaldehydes

Butyllithium (1.6 M solution in hexane, 0.063 mL, 0.10 mmol) was added to a solution of bis(trimethylsilyl) sulfide (178 mg, 1.0 mmol) in THF (30 mL) at 0°C under nitrogen. After stirring for 30 min at 0°C, a dienal (1.05 mmol) was added. The reaction mixture was heated under reflux for 6 h. Evaporation of the solvent followed by a flash column chromatography on silica gel (hexane as eluent) yielded 2-thiabicyclo[4.n.0]alk-4-ene derivative as a mixture of cis and trans isomers.

2-Thiabicyclo[4.3.0]non-4-ene (cis:trans=67:33)



cis

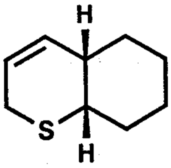


trans

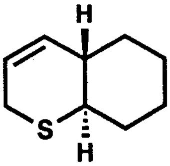
^{1}H-NMR cis δ 1.52-2.11(m, 1H), 2.43(br s, 1H), 2.90(dd, 1H, J_1=4.9Hz, J_2=17.4Hz), 3.17(ddd, 1H, J_1=2.4Hz, J_2=5.2Hz, J_3=17.4Hz), 3.22(ddd, 1H, J_1=4.0Hz, J_2=6.1Hz, J_3=7.6Hz), 5.80(ddt, 1H, J_1=4.0Hz, J_2=10.4Hz, J_3=1.8Hz), 5.86(dddd, 1H, J_1=1.8Hz, J_2=3.1Hz, J_3=5.2Hz, J_4=10.4 Hz)

trans δ 1.13-1.24(m, 1H), 1.37-1.48(m, 1H), 1.53-2.15(m, 5H), 2.53(ddd, 1H, J_1=6.7Hz, J_2=10.4Hz, J_3=11.9Hz), 3.08 (ddt, 1H, J_1=4.6Hz, J_2=17.4Hz, J_3=2.4 Hz), 3.49(ddt, 1H, J_1=3.7Hz, J_2=17.4Hz, J_3=2.4Hz), 5.70(ddt, 1H, J_1=4.6Hz, J_2=10.4Hz, J_3=2.4Hz), 5.91(br d, 1H, J=10.4Hz)

2-Thiabicyclo[4.4.0]oct-4-ene (cis:trans=54:46)



cis

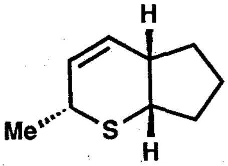


trans

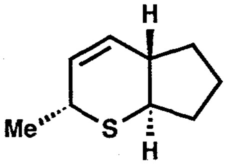
^{1}H-NMR cis δ 1.27-1.91(m, 8H), 2.42(br s, 1H), 3.04(br dd, 1H, J_1=5.8Hz, J_2=9.8Hz), 3.09(ddt, 1H, J_1=4.0Hz, J_2=17.4Hz, J_3=2.1Hz), 3.22(br d, 1H, J=17.4Hz), 5.64(ddt, 1H, J_1= 4.0Hz, J_2=10.7Hz, J_3=2.1Hz), 5.79(ddt, 1H, J_1=2.1Hz, J_2= 10.7Hz, J_3=4.0Hz).

trans δ 1.02-1.13(m, 1H), 1.25-1.43(m, 3H), 1.72-1.85(m, 3H), 1.90(br d, 1H, J=11.0Hz), 2.08(m, 1H), 2.50(ddd, 1H, J_1=3.4Hz, J_2=9.8Hz, J_3=11.9Hz), 2.95(ddt, 1H, J_1= 5.2Hz, J_2=17.4Hz, J_3=2.1Hz), 3.52(ddt, 1H, J_1=4.0Hz, J_2= 17.4Hz, J_3=2.4Hz), 5.53(ddd, 1H, J_1=2.1Hz, J_2=4.0Hz, J_3= 10.4Hz) 5.74 (ddt, 1H, J_1=5.2Hz, J_2=10.4Hz, J_3=2.6Hz).

3-Methyl-2-thiabicyclo[4.3.0]non-4-ene (cis:trans=53:47)



cis

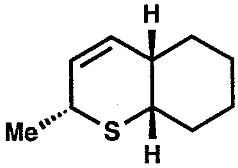


trans

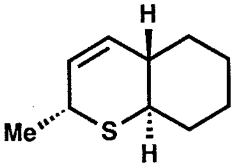
^{1}H-NMR cis δ 1.26(d, 3H, J=7.0Hz), 1.20-2.16(m, 6H), 2.32(br s, 1H), 3.44-3.55(m, 2H), 5.67(dt, 1H, J_1=10.7Hz, J_2=1.8Hz) 5.83(ddd, 1H, J_1=2.4Hz, J_2=4.6Hz, J_3=10.7 Hz).

trans δ 1.42(d, 3H, J=7.0Hz), 1.16-2.10(m, 7H), 2.54 (ddd, 1H, J_1=6.7Hz, J_2=10.4Hz, J_3=11.9Hz), 3.40-3.60(m, 1H), 5.64(ddd, 1H, J_1=2.7Hz, J_2=4.0Hz, J_3= 10.7Hz), 5.89 (br d, 1H, J=10.7Hz).

3-Methyl-2-thiabicyclo[4.4.0]oct-4-ene (cis:trans=62:38)



cis



trans

^{1}H-NMR cis δ 1.28(d, 3H, J=7.0Hz), 1.23-1.92(m, 8H), 2.15(br s, 1H), 3.30-3.33(m, 1H), 3.62-3.69(m, 1H), 5.57(dt, 1H, J_1 =10.7Hz, J_2=1.8Hz), 5.65(ddd, 1H, J_1=2,4Hz, J_2=4.9Hz, J_3 =10.7Hz).

trans δ 1.42(d, 3H, J=7.0Hz), 1.02-1.12(m, 1H), 1.27-1.43(m, 3H), 1.73-1.89(m, 4H), 1.94-2.03(m, 1H), 2.50 (ddd, 1H, J_1=3.3Hz, J_2=10.1Hz, J_3=11.3Hz), 3.24-3.35(m, 1H), 5.48(br d, 1H, J=10.7Hz), 5.68(ddd, 1H, J_1=2.8Hz, J_2=4.6Hz, J_3=10.7Hz).

General Procedure for Wittig Reaction of Thioaldehydes

To a solution of bis(trimethylsilyl) sulfide (178 mg, 1.0 mmol) in THF (30 mL) was added butyllithium (1.6 M solution in hexane, 63 L, 0.1 mmol) at 0 °C, and after 30 min at 0 °C, benzaldehyde (106 mg, 1.0 mmol) was added. After the confirmation of the complete consumption of benzaldehyde and bis(trimethylsilyl) sulfide by TLC and ^{1}H-NMR measurement, respectively, the resulting solution was added dropwise to an ylide solution, which was easily prepared by the reaction of a phosphonium halide with butyllithium in THF, with vigorous stirring at room temperature. After an additional 12 h, evaporation of the solvent followed by a flash column chromatography on silica gel (benzene as eluent) yielded the Wittig-type product and triphenylphosphine sulfide.

3-7 References and Notes

(1) Reviews: Organic Compounds of Sulphur, Selenium, and Tellurium; Specialist Periodical Reports; The Chemical Society: London, 1970-1981; Vols. 1-6. Boger, D. L.; Weinreb, S. M. Hetero Diels-Alder Methodology in Organic Synthesis; Academic Press: 1987, 120.

(2) Okazaki, R. J. Synth. Org. Chem. Jpn. 1988, 46, 1149.

(3) Mackie, R. K.; McKenzie, S.; Reid, D. H.; Webster, R. G. J. Chem. Soc., Perkin Trans. 1 1973, 657.

(4) (a) Okazaki, R.; Ishii, A.; Fukuda, N.; Oyama, H.; Inamoto, N. J. Chem. Soc., Chem. Commun. 1982, 1187. (b) Okazaki, R.; Ishii, A.; Inamoto, N. J. Am. Chem. Soc. 1987, 109, 279.

(5) (a) Vedejs, E.; Eberlein, T. H.; Varie, D. L. J. Am. Chem. Soc. 1982, 104, 1445. (b) Vedejs, E.; Perry, D. A. Ibid. 1983, 105, 1683. (c) Vedejs, E.; Perry, D. A.; Houk, K. N.; Rondan, N. G. Ibid. 1983, 105, 6999. (d) Vedejs, E.; Eberlein, T. H.; Mazur, D. J.; McClure, C. K.; Perry, D. A.; Ruggeri, R.; Schwartz, E.; Stults, J. S.; Varie, D. L.; Wilde, R. G.; Wittenberger, S. J. Org. Chem. 1986, 51, 1556. (e) Vedejs, E.; Perry, D. A.; Wilde, R. G. J. Am. Chem. Soc. 1986, 108, 2985. (f) Vedejs, E.; Fedde, C. L.; Schwartz, C. E. J. Org. Chem. 1987, 52, 4269. (g) Vedejs, E.; Eberlein, T. H.; Wilde, R. G. Ibid. 1988, 53, 2220. (h) Vedejs, E.; Stults, J. S.; Wilde, R.

G. J. Am. Chem. Soc. 1988, 110, 5452.

(6) (a) Baldwin, J. E.; Lopez, R. C. G. J. Chem. Soc., Chem. Commun. 1982, 1029. Idem, Tetrahedron 1983, 39, 1487. (b) Bladon, C. M.; Freguson, I. E. G.; Kirby, G. W.; Lochead, A. W.; McDougall, D. C. J. Chem. Soc., Perkin Trans. 1 1985, 1541. (c) Krafft, G. A.; Meinke, P. T. Tetrahedron Lett. 1985, 26, 1947. (d) Schaumann, E.; Ruhter, G. Ibid. 1985, 26, 5265. (e) Lee, L. F.; Dolson, M. G.; Howa, R. K.; Stults, B. R. J. Org. Chem. 1985, 50, 3216. (f) Wilson, S. R.; Georgiadis, G. M.; Khatri, H. N.; Bartmess, J. E. J. Am. Chem. Soc. 1980, 102. 3577. (g) Reich, H. J.; Jaspers, C. P. Ibid. 1987, 109, 5549. (h) Buchwald, S. L.; Nielsen, R. B. Ibid. 1988, 110, 3171. (i) Steliou, K.; Mrani, M. Ibid. 1982, 104, 3104. (j) Ricci, A.; Degl'Innocenti, A.; Capperucci, A.; Reginato, G. J. Org. Chem. 1989, 54, 20. (k) Okuma, K.; Tachibana, Y.; Sakata, J.; Komiya, T.; Kaneko, I.; Komiya, Y.; Yamasaki, S.; Yamamoto, S.; Ohta, H. Bull. Chem. Soc. Jpn. 1988, 61, 4323.

(7) (a) Segi, M.; Nakajima, T.; Suga, S.; Murai, S.; Ryu, I.; Ogawa, A.; Sonoda, N. J. Am. Chem. Soc. 1988, 110, 1976. (b) Segi, M.; Takahashi, M.; Nakajima, T.; Suga, S.; Murai, S.; Sonoda, N. Tetrahedron Lett. 1988, 29, 6965.

(8) Detty, M. R.; Seidler, M. D. J. Org. Chem. 1982, 47, 1354.

(9) Buchi, G.; Wuest, H. J. Org. Chem. 1969, 34, 1122.

(10) Vedejs, E.; Arnost, M. J.; Hagen, J. P. J. Org. Chem.

1979, 44, 3230.

(11) Schneider, M. P.; Goldbach, M. J. Am. Chem. Soc. 1980, 102, 6114.

(12) Roush, W. R.; Gillis, H. R.; Ko, A. I. J. Am. Chem. Soc. 1982, 104, 2269.

(13) (a) Denny, B.; Ross, S. T.; J. Org. Chem. 1962, 27, 998. (b) Grayson, M.; Keough, P. T. J. Am. Chem. Soc. 1960, 82, 3919.

Chapter 4. Synthesis and Diels-Alder Reaction of Thioketones

4-1 Introduction

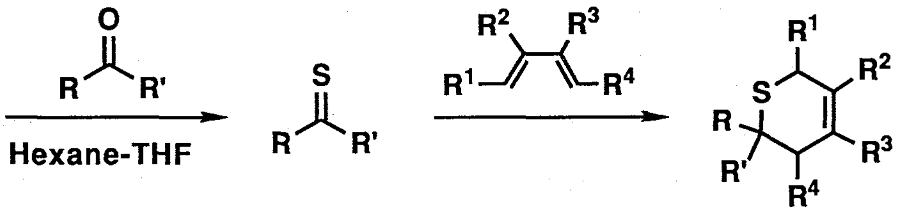
Thioketone chemistry has been for a long time studied as one of the useful intermediates in organic synthesis.[1] It is well known that thioketones are easily prepared from ketones using various sulfurating reagents,[2] for example H_2S, P_2S_5, Lawesson reagent, etc, and react with a diene to give the corresponding Diels-Alder adducts.[3] However, there are few reports of study on stereo- or regio-chemistry of thioketone cycloaddition reactions.[4]

Chapters 1-3 described novel syntheses of selenoaldehydes, selenoketones, and thioaldehydes by use of the new selenating and sulfurating reagents, which take advantage of the large affinity of silicon or aluminum to oxygen atom. As a line in our studies on a series of reactive compounds containing carbon-chalcogen double bond, generation of thioketones, using bis(dimethylaluminum) sulfide as a sulfurating reagent, and stereochemistry of their Diels-Alder reactions with a diene were investigated.

4-2 Generation and Diels-Alder Reaction of Thioketones

Bis(dimethylaluminum) sulfide 1,[5] formed in situ via Sn-Al exchange reaction of bis(tributyltin) sulfide with trimethylaluminum in hexane, reacted with various ketones in the presence of 1,3-diene in a THF/hexane mixed solvent to give Diels-Alder sdducts of the corresponding thioketones with the diene (eq. 4-1). These results are summarized in Tables 4-1, 4-2, and 4-3. Satisfactory results on yields of cycloadducts were obtained as a whole. When acylsilanes were used as a starting ketone, the Diels-Alder reaction of thioacylsilanes, a closely related but only recently explored class of exotic molecules,[6] with cyclopentadiene proceeded efficiently to give the cycloadducts in good yields. Accordingly, this method using 1 as a sulfurating reagent offered an alternative convenient route to thioketones.

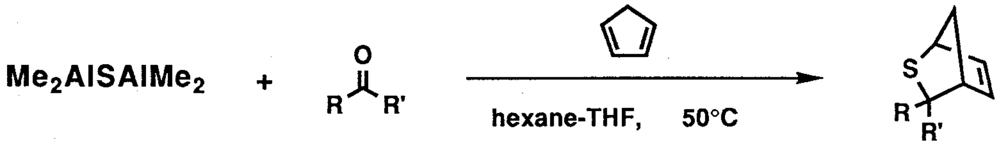
$$\mathrm{Bu_3SnSSnBu_3} + \mathrm{2Me_3Al} \xrightarrow[\text{Hexane, 50°C}]{-\,\mathrm{2Bu_3SnMe}} \mathrm{Me_2AlSAlMe_2}$$



(4-1)

Stereo- and regiochemistry of the Diels-Alder reaction of

Table 4-1. Generation and Diels-Alder Reaction of Thioketones in the Presence of Cyclopentadiene Using 1



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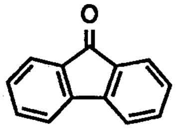
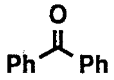
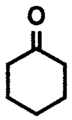
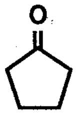
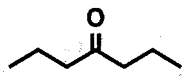
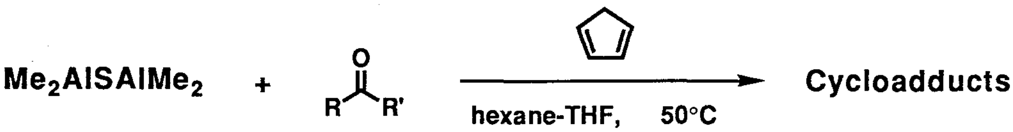
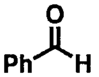
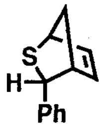
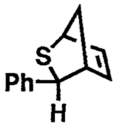
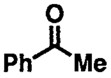
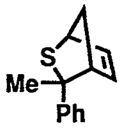
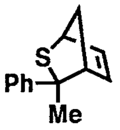
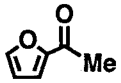
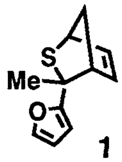
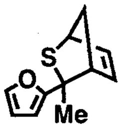
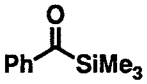
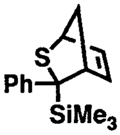
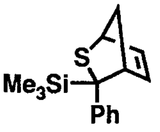
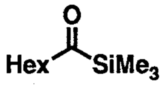
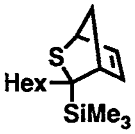
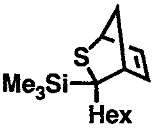
1		4.0	84
2		3.5	73
3		3.0	88
4		4.0	57
5		4.0	60
6		4.0	87

[a] Isolated yield.

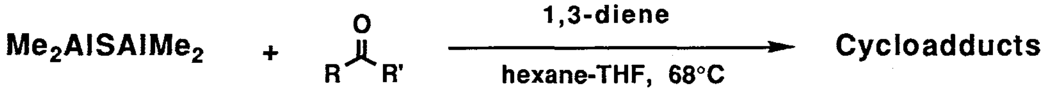
Table 4-2. Diels-Alder Reaction of Unsymmetrical Thioketones with Cyclopentadiene

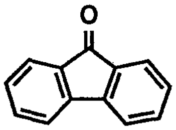
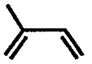
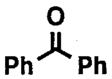
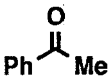
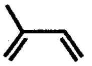
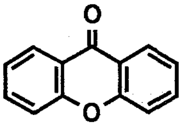
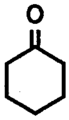
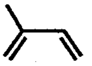
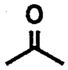


entry	RR'C=O	time (h)	adduct isomer ratio	yield[b] (%)
7		6.0	  3 : 1	80
8		5.0	  1 : 1	99
9		1.2	  1 : 1	73
10		4.0	  4.3 : 1	99
11		1.0	  1.1 : 1	90

[a] Determined by ^{1}H-NMR. [b] Isolated yield.

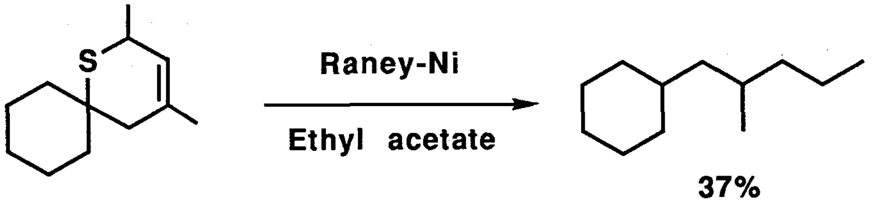
Table 4-3. Diels-Alder Reaction of Thioketones with an Acyclic 1,3-Diene



entry	RR'C=O	diene	time (h)	yield[a] (%)
12			5	80
13			5	99
14			3	81
15			4	84
16			7	76
17			23	87
18			6	32
19			6	30

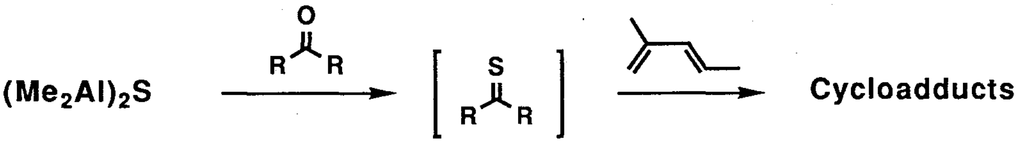
[a] Isolated yield.

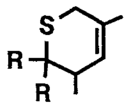
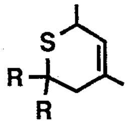
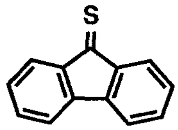
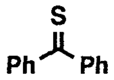
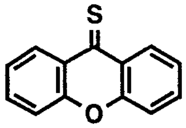
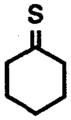
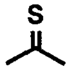
thioketones are interesting problem. The cycloaddition of unsymmetrical thioketones with cyclopentadiene proceeded with a less stereoselectivity (Table 4-2). Vedejs et al reported that observation of the endo preferences in Diels-Alder reaction of thioaldehydes with cyclopentadiene is primarily due to steric effects of substituents and positive frontier orbital interactions (secondary orbital overlap).[7] In the examples in Table 4-2, both of two substituents of ketones may be responsible for the endo preferences. So, no stereoselectivity would be seemingly observed in this Diels-Alder reaction. On the other hand, high regioselectivity was exhibited in the Diels-Alder reaction of thioketones with 2-methyl-1,3-pentadiene (Table 4-4). Cycloaddition reaction of aromatic thioketones such as thiofluorenone gave "meta" type adducts as the predominant regioisomer. This regiochemistry is similar to that observed in analogous reactions of selenofluorenone.[8] Interestingly, the aliphatic substituents reversed the regiochemistry to give a predominant "ortho-para" isomers. The structure of the adduct obtained from the Diels-Alder reaction of thioketones was determined by reductive desulfurization with Raney-Ni to the hydrocarbon followed by ^{13}C-NMR analysis (eq. 4-2). Further



(4-2)

Table 4-4. Regiochemistry of Diels-Alder Reaction of Thioketones with 2-Methyl-1,3-pentadiene



		:	 [a]
	> 99	:	1
	94	:	6
	91	:	9
	1	:	> 99
	1	:	> 99
	9	:	91

[a] Determined by ^{1}H-NMR.

investigations will bring about more accurate interpretations on stereochemistry of thioketone cycloaddition.

4-3 Experimental

Apparatus

Infrared spectra were obtained on a JASCO A-202 spectrometer and absorptions are reported in reciprocal centimeters. ^{1}H-NMR spectra were determined on a JEOL JX-100F or a JEOL JNM-GX-400 spectrometer and are reported in parts per million (δ) downfield from internal tetramethylsilane (TMS) in $CDCl_3$. Data are reported as follows: chemical shift, multiplicity (s= singlet, d=doublet, t=triplet, q=quartet, m=multiplet, br= broad), coupling constant (Hz), integration, and interpretation. Mass spectra were recorded on a Hitachi M-80 spectrometer.

Materials

Tetrahydrofuran (THF) was freshly distilled from potassium /benzophenone just prior to use. Hexane and toluene were also distilled from calcium hydride just prior to use. Cyclopentadiene was obtained by heating (160-180 °C) technical dicyclopentadiene carefully under a fractionating column. The other dienes and ketones were purchased from commercial sources and purified by distillation. Bis(tributyltin) sulfide was prepared according to the reported procedure.[9]

General Procedure for the Generation and Trapping of Thioketones Using Bis(dimethylaluminum) Sulfide

A typical experimental procedure is exemplified by the synthesis of a thiofluorenone cycloadduct. Trimethylaluminum (1.0 M solution in hexane, 2.2 mL, 2.2 mmol) was added to a solution of bis(tributyltin) sulfide (612 mg, 1.0 mmol), bp 164-166 °C (0.1 mmHg), easily prepared by the reaction of $Na_2S \cdot 9H_2O$ and n-Bu_3SnCl,[9] in hexane (15 mL) under argon and the mixture was stirred for 15 h at 50 °C. After the addition of THF (20 mL) as a co-solvent, cyclopentadiene (660 mg, 10 mmol) and fluorenone (216 mg, 1.2 mmol) were added in that order. The mixture was subsequently heated at 50 °C for 4 h and then worked up with water. After extraction with ether the combined extracts were dried, concentrated, and purified by flash column chromatography on silica gel (hexane: dichloromethane=2:1 as eluent) to give the thiofluorenone cycloadduct (220 mg, 84% yield).

All cycloadducts were gave satisfactory IR, ^1H-NMR, and mass spectral data.

4-4 References and Notes

(1) Organic Compounds of Sulphfur, Selenium, and Tellurium; Specialist Periodical Reports; The Chemical Society: London, 1970-1981; Vols. 1-6.

(2) (a) Lecher, H. Z.; Greenwood, R. A.; Whitehouse, K. C.; Chao, T. H. J. Am. Chem. Soc. 1956, 78, 5018. (b) Walter, W.; Proll, T. Synthesis 1979, 941. (c) Shabana, R.; Rasmussen, J. B.; Lawesson, S. O. Bull. Soc. Chim. Belg. 1981, 90, 75, and references cited therein.

(3) Boger, D. L.; Weinreb, S. M. Hetero Diels-Alder Methodology in Organic Synthesis; Academic Press: 1987, 120. Larson, S. D. J. Am. Chem. Soc. 1988, 110, 5932.

(4) (a) Ohno, A.; Ohnishi, Y.; Tsuchihashi, G. Tetrahedron 1969, 25, 871. (b) Katada, T.; Eguchi, S.; Esaki, T.; Sasaki, T. J. Chem. Soc., Perkin Trans. 1 1984, 1869. (c) Katada, T.; Eguchi, S.; Sasaki, T. J. Org. Chem. 1986, 51, 314.

(5) For the early synthesis and reactions of bis(diethylaluminum) sulfide, see: Imaeda, H.; Hirabayashi, T.; Itoh, K.; Ishii, Y. Organometal. Chem. Syn. 1970/1971, 1, 115.

(6) (a) Bonini, B. F.; Mazzanti, G.; Sarti, S.; Zanirato, P.; Maccagnani, G. J. Chem. Soc., Chem. Commun. 1981, 822. (b) Barbaro, G.; Battaglia, A.; Giorgianni, P.; Maccagnani, G.; Macciantelli, D.; Bonini, B. F.; Mazzanti, G.; Zanirato, P. J. Chem. Soc., Perkin Trans. 1 1986, 381. (c) Ricci, A.; Degl'Innocenti,

A.; Seconi, G.; Dembech, P.; Ramadan, N.; Walton, D. R. M. Tetrahedron Lett. 1985, 26, 1091. (d) Ricci, A.; Degl'Innocenti A.; Capperucci, A.; Reginato, G. J. Org. Chem. 1989, 54, 19.

(7) Vedejs, E.; Stults, J. S.; Wilde, R. G. J. Am. Chem. Soc. 1988, 110, 5452.

(8) (a) Meinke, P. T.; Krafft, G. A.; Spencer, J. T. Tetrahedron Lett. 1987, 28, 3887. (b) Meinke, P. T.; Krafft, G. A. J. Am. Chem. Soc. 1988, 110, 8679. (c) Segi, M.; Koyama, T.; Nakajima, T.; Suga, S.; Murai, S.; Sonoda, N. Tetrahedron Lett. 1989, 30, 2095.

(9) Abel, E. W.; Armitage, D. A. Adv. Organometl. Chem. 1967, 5, 1.

Chapter 5. A New Route to Telluro-aldehydes and -ketones Using Bis(dimethylaluminum) Telluride

5-1 Introduction

Studies on the chemistry containing the tellurocarbonyl group have been rather tardy because of much more lability of carbon-tellurium double bond.[1] Telluro-esters and -amides, stabilized by resonance delocalization of oxygen and nitrogen lone pair electrons onto tellurium, and stable tellurocarbonyl compounds coordinated to the transition metals have been reported since 1979,[2-5] whereas generation of "free" telluroaldehydes and -ketones have not been known hitherto and therefore remain a challenge for synthesis. Recently we have described simple and convenient methods for selenoaldehyde[6] and selenoketone[7] generations, in which bis(trimethylsilyl) selenide ($Me_3SiSeSiMe_3$) and bis(dimethylaluminum) selenide (Me_2Al-$SeAlMe_2$) were used as selenating reagents, respectively. The tellurium analogue of the former, however, was by no means effective for generation of tellurocarbonyl compounds. Now we have found that bis(dimethylaluminum) telluride ($Me_2AlTeAlMe_2$, **1**) can serve as an efficient tellurating reagent for the direct conversion of aldehydes and ketones to telluro-aldehydes and

-ketones. While this work was in progress, Erker and Hock reported generation of tellurobenzaldehyde using the reaction of a phosphorus ylide with tellurium. They described only one example with low yield (11%).[8] In this chapter the first general method for the generation of both telluroaldehydes and telluroketones is described.

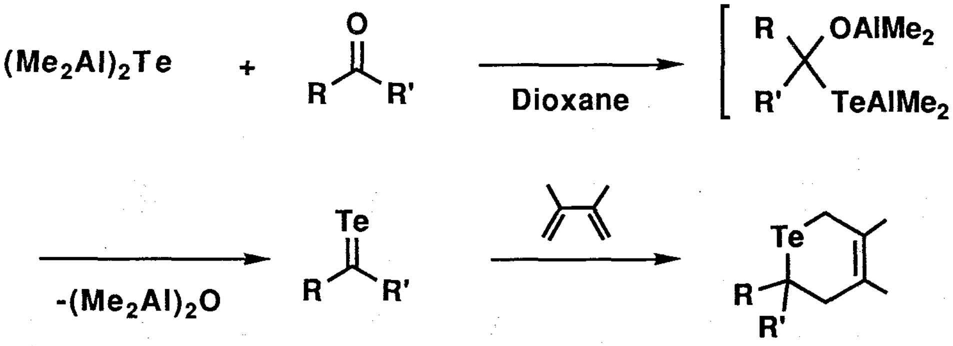
5-2 Generation and Trapping of Telluro-aldehydes and -ketones Using Bis(dimethylaluminum) Telluride

The preparation of a new tellurating reagent **1** was initially attempted by the reaction of bis(trimethylsilyl) telluride[9] with dimethylaluminum chloride. Unfortunately, **1** obtained via this Si-Al metal exchange was not effective for the telluration of aldehydes or ketones and immediate deposition of elemental tellurium was observed. The mischief would be due to trimethylsilyl chloride formed at the stage of transmetallation. We chose then a Sn-Al metal exchange for the synthesis of **1**. Thus, **1** was synthesized by the transmetallation reaction of bis(tributyltin) telluride with 2.0 equivalent of trimethylaluminum in toluene, as shown in eq. 5-1. Quantitative formation of tetramethyltin was shown by ^{1}H-NMR measurement for the run using bis(trimethyltin) telluride. The reagent **1** in toluene was likely to exist in the aggregated form since the reaction mixture turned into a opaque suspension.

$$\mathrm{Bu_3SnTeSnBu_3} + \mathrm{2Me_3Al} \xrightarrow[\text{90 °C}]{} \text{Toluene}$$

$$\underset{\mathbf{1}}{\mathrm{Me_2AlTeAlMe_2}} + \mathrm{2Bu_3SnMe} \qquad (5\text{-}1)$$

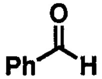
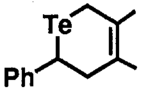
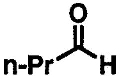
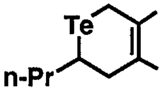
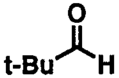
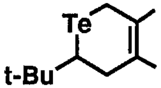
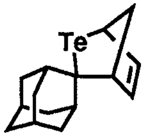
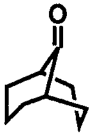
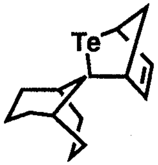
This suspension reacted with aldehydes only very slowly. So, after the removal of toluene, dioxane was added and used as a solvent to result in a homogeneous system. The reaction of 1 with aldehydes or ketones was carried out in refluxing dioxane in the presence of a diene (eq. 5-2).



(5-2)

Heating 1 with benzaldehyde in the presence of excess 2,3-dimethyl-1,3-butadiene in refluxing dioxane for 6 h afforded the Diels-Alder adduct of the corresponding tellurobenzaldehyde in 49% yield. This indicates that the telluroaldehyde is efficiently formed in situ. Further examples of the reaction of 1 with aldehydes or ketones are summarized in Table 5-1. For telluroketone synthesis, the success depended upon a structural factor. When moderately sterically hindered ketones

Table 5-1. Generation and Cycloaddition of Telluro-aldehydes and -ketones

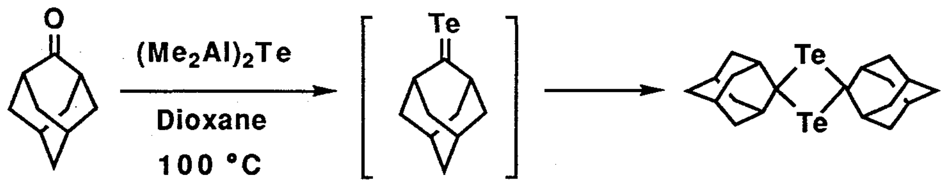
entry	substrate	solvent	condition, (°C,h)	diene	cycloadduct	yield[a] (%)
1		Dioxane	100, 2.0			49
2		THF	66, 2.0			26
3		Dioxane	100, 2.0			44
4		Dioxane	100, 3.0			62
5		Dioxane	100, 3.0			55
6		THF	66, 3.0			24
7		Dioxane	100, 2.0			52

[a] Isolated yield.

such as adamantanone and bicyclo[3.3.1]nonan-9-one were used, the efficient trapping of the corresponding telluroketones by cyclopentadiene was observed (entries 5 and 7). All cycloadducts obtained were not so much sensitive to air and light, but decomposed under an acidic condition with deposition of elemental tellurium.

The high reaction temperature caused by refluxing dioxane is essential for the generation of tellurocarbonyl compounds by the use of 1 compared with entries 2 and 6 using THF. This reaction may involve the initial coordination of aluminum of 1 to carbonyl oxygen followed by intramolecular transfer of the tellurium group to electropositive carbonyl carbon center. Thermodynamically stable Al-O-Al bond formation then leads to the construction of carbon-tellurium double bond.

In the absence of a diene, 1 reacted with adamantanone to give a dimer of telluroadamantanone in 28% yield (eq. 5-3). The mass spectrum of this compound supported the dimeric molecular formula of $C_{20}H_{28}Te_2$ with a molecular ion at m/e=528 (Te^{130}) having the expected isotope pattern for Te_2.



(5-3)

5-3 Experimental

Apparatus

Melting points were recorded on a Yanagimoto MP-S2 melting point apparatus. Melting points are uncorrected. ^{1}H- and ^{13}C-NMR spectra were determined on a JEOL JNM-GX-400 spectrometer at 399.65 and 100.40 MHz, respectively, and are reported in parts per million (δ) downfield from internal tetramethylsilane (TMS) in $CDCl_3$. Data are reported as follows: chemical shift, multiplicity (s=singlet, d=doublet, t=triplet, q=quartet, m= multiplet, br=broad), coupling constant (Hz), integration, and interpretation. Infrared spectra were obtained on a JASCO A-202 spectrometer and absorptions are reported in reciprocal centimeters. Mass spectra were recorded on a JEOL JMS-DX303 or a Hitachi M-80 spectrometer. Elemental analyses were performed on a Yanagimoto CHN-Corder MT-2.

Materials

Tetrahydrofuran (THF) was freshly distilled from potassium /benzophenone just prior to use. Super Hydride® and chloroform-d were purchased from Aldrich Chemicals, Ltd. and used without purification. Trimethylaluminum was purchased from Kanto Chemical Co., Inc. and used without purification.

Metallic tellurium (99.999%) was purchased from Nakarai Chemicals, Ltd. Cyclopentadiene was obtained by heating (160-180 °C) technical dicyclopentadiene carefully under a fractionating column. The other dienes, ketones, and tributyltin chloride were purchased from commercial sources and purified by distillation or recrystallization.

<u>Preparation of Bis(tributyltin) Telluride 1</u>

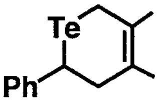
A 50-mL three-necked, round-bottomed flask was flamed and cooled under an argon atmosphere. The flask was wrapped in foil and then charged with lithium triethylborohydride (Super Hydride®)(1.0 M solution in THF, 33 mL, 33 mmol). The frask was cooled in an ice bath, and tellurium (Nakarai Chemicals, Ltd., 99.999%, 1.9 g, 15 mmol) was added in portions. The reaction mixture was warmed to room temperature and stirred for 8 h. The reaction mixture was cooled to ice-bath temperature, and tributyltin chloride (10.7 g, 33 mmol) was added in one portion. The reaction mixture was warmed to room temperature and stirred for 12 h. The low-boiling volatiles were removed by a careful reduced distillation at 30-60 °C (20 mmHg) directly from the reaction vessel. The product 1 was subsequently distilled at higher vacuum, again directly from the reaction vessel, to give 10.1 g (95% yield) of 1 as a colorless oil, bp 165-168 °C (0.2 mmHg). The receiving flask was foil wrapped to minimize exposure to light.

In a similar manner, bis(trimethyltin) telluride was obtained in 78% yield, bp 63-65 °C (0.3 mmHg). ^{1}H-NMR ($CDCl_3$) δ 0.61 (s).

General Procedure for the Generation and Trapping of Telluroaldehydes and -ketones Using Bis(dimethylaluminum) Telluride

A typical experimental procedure is exemplified by the synthesis of a tellurobenzaldehyde cycloadduct. Trimethylaluminum (1.0 M solution in hexane, 1.4 mL, 1.4 mmol) was added to a solution of bis(tributyltin) telluride (424 mg, 0.6 mmol), bp 165-168 °C/0.2 mmHg, easily prepared by the reaction of Li_2Te and n-Bu_3SnCl, in toluene (10 mL) under argon and the mixture was stirred for 15 h at 90 °C. After the removal of toluene carefully under reduced pressure, dioxane (15 mL) as solvent, 2,3-dimethyl-1,3-butadiene (246 mg, 3.0 mmol), and benzaldehyde (106 mg, 1.0 mmol) were added in that order. The mixture was subsequently heated under reflux for 6 h and poured into water. Usual workup followed by flash column chromatography on alumina (hexane: dichloromethane=5:1) furnished the Diels-Alder adduct of tellurobenzaldehyde in 49% yield.

3,6-Dihydro-4,5-dimethyl-2-phenyl-2H-telluropyran



^{1}H-NMR δ 7.14-7.40(m, 5H, ArH), 4.87(dd, J_1=3.4Hz, J_2=11.0Hz, 1H, C-2), 3.85(br d, J=11.9Hz, 1H, C-6), 3.14(br d, J=11.9Hz, 1H, C-6), 3.04(br dd, J_1=11.0Hz, J_2=13.7Hz, 1H, C-3), 2.48(dd, J_1=3.4Hz, J_2=13.7Hz, 1H, C-3), 1.87 (br s, 3H, Me), 1.85(br s, 3H, Me).

^{13}C-NMR δ 145.6, 132.4(s, C4, C5), 129.6(s), 128.5(d), 127.7 (d), 126.3(d), 42.7(t, C3), 34.7(d, C2), 20.4, 18.3(q, 2Me), 4.3(t, C6).

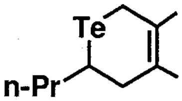
IR (NaCl, neat) 2955, 2852, 1460, 1390, 1362, 1240, 1142, 1120, 1055, 896 cm^{-1}.

MS, m/e 302(M$^+$), 220, 171(base peak), 143, 129, 115, 91.

Exact MS, Calcd for $C_{13}H_{16}Te(Te^{130})$: 302.0319.

Found: 302.0342.

3,6-Dihydro-4,5-dimethyl-2-n-propyl-2H-telluropyran



^{1}H-NMR δ 3.87(ddt, J_1=8.2Hz, J_2=10.4Hz, J_3=4.3Hz, 1H, C-2), 3.31(br d, J=11.6Hz, 1H, C-6), 3.15(br d, J=11.6Hz, 1H, C-6), 2.45 (br dd, J_1=8.2Hz, J_2=13.7Hz, 1H, C-3), 2.38(br dd, J_1=4.3Hz, J_2=13.7Hz, 1H, C-3), 1.85(br s, 3H, Me), 1.81(br s, 3H, Me), 1.32-76(m, 4H), 0.91(t, J=7.3Hz, 3H).

^{13}C-NMR δ 131.7, 129.6(s, C4, C5), 41.9, 41.4(t, C3 and α-CH$_2$ of n-Pr), 35.0(d, C2), 24.3(t, β-CH$_2$ of n-Pr), 20.9, 17.8, 13.9 (q, 3Me), 1.5(t, C6).

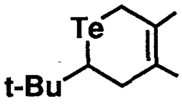
IR (NaCl, neat) 2950, 2928, 2852, 1448, 1374, 1255, 1157, 882 cm^{-1}.

MS, m/e 268(M$^+$), 257, 185, 137, 109, 95, 69, 55(base peak).

Exact MS, Calcd for $C_{10}H_{18}Te(Te^{130})$: 268.04755.

Found: 268.0496.

3,6-Dihydro-2-t-butyl-4,5-dimethyl-2H-telluropyran



^{1}H-NMR δ 3.62(dd, J_1=3.1Hz, J_2=12.2Hz, 1H, C-2), 3.60(br d, J=11.9 Hz, 1H, C-6), 2.76(br d, J=11.9Hz, 1H, C-6), 2.53(br dd, J_1= 12.2Hz, J_2=13.7Hz, 1H, C-3), 2.20(br dd, J_1=3.1Hz, J_2=13.7 Hz, 1H, C-3), 1.86(br s, 3H, Me), 1.77(br s, 3H, Me), 1.09 (s, 9H, t-Bu).

^{13}C-NMR δ 132.9, 129.7(s, C4, C5), 51.5(d, C2), 36.9(t, C3), 35.2 (s, t-Bu), 29.4(q, 3Me of t-Bu), 19.7, 17.9(q, 2Me), 1.5(t, C6).

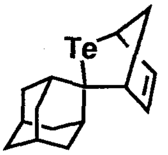
IR (NaCl, neat) 3020, 2915, 2846, 1595, 1490, 1442, 1375, 1240, 1120, 1070, 1025, 757, 695 cm^{-1}.

MS, m/e 282(M^+), 257, 109, 95, 81, 69(base peak), 57.

Exact MS, Calcd for $C_{11}H_{20}Te(Te^{130})$: 282.0632.

Found: 282.0649.

Spiro[adamantane-2,3'-2'-tellurabicyclo[2.2.1]hept-5'-ene]



Mp 56-57 °C.

^{1}H-NMR δ 6.43(dd, J_1=2.8Hz, J_2=5.2Hz, 1H, C-6), 5.66(dd, J_1=3.4Hz, J_2=5.2Hz, 1H, C-5), 4.63(br s, 1H, C-1), 2.58 (br s, 1H, C-4), 1.61-2.44(m, 16H, C-7 and AdH).

^{13}C-NMR δ 141.1, 129.9(d, C5, C6), 87.7(s, C3), 54.1(t, C7), 51.9(d, C4), 44.9(t), 43.0(t), 40.4(d), 39.5(t), 38.0 (d), 35.5(t), 35.1(t), 32.3(d, C1), 27.0(d), 26.3(d).

IR (NaCl, neat) 2920, 2850, 1640, 1454, 1440, 1338, 1268, 1196, 1153, 1097, 1042, 904, 870, 742, 730 cm^{-1}.

MS, m/e 330(M^+), 264, 199(base peak), 171, 157, 143, 135, 117, 105, 91, 79, 67.

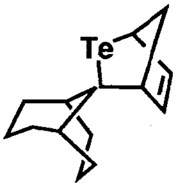
Exact MS, Calcd for $C_{15}H_{20}Te(Te^{130})$: 330.0632.

Found: 330.0640.

Anal. Calcd for $C_{15}H_{20}Te$: C, 54.94; H, 6.15.

Found: C, 55.08; H, 6.16.

Spiro[bicyclo[3.3.1]nonane-9,3'-2'-tellurabicyclo[2.2.1]hept-5'-ene]



Mp 35-37 °C.

^{1}H-NMR δ 6.45(dd, J_1=2.7Hz, J_2=5.2Hz, 1H, C-6), 5.67(dd, J_1= 3.4Hz, J_2=5.2Hz, 1H, C-5), 4.60(br s, 1H, C-1), 2.64 (br s, 1H, C-4), 1.38-2.35(m, 16H).

^{13}C-NMR δ 141.4, 129.9(d, C5, C6), 86.5(s, C3), 53.7(t, C7), 51.5(d, C4), 40.1(d), 39.9(t), 37.9(d), 37.0(t), 32.0 (d, C1), 29.6 (t), 28.7(t), 20.3(t), 20.2(t).

IR (NaCl, neat) 3050, 2920, 2840, 1640, 1488, 1452, 1438, 1340, 1266, 1042, 914, 840, 742, 730 cm^{-1}.

MS, m/e 318(M^+), 252, 196, 187, 159, 145, 121(base peak), 105, 91, 79, 67.

Exact MS, Calcd for $C_{14}H_{20}Te(Te^{130})$: 318.0632.

Found: 318.0626.

Anal. Calcd for $C_{14}H_{20}Te$: C, 53.23; H, 6.38.

Found: C, 52.77; H, 6.29.

5-4 References and Notes

(1) Guziec, Jr., F. S. The Chemistry of Organic Selenium and Tellurium Compounds; Patai, S., Ed.; John Wiley & Sons: New York, 1987; Vol. 2; pp 215-273.

(2) For telluroesters: (a) Barrett, A. G. M.; Barton, D. H. R.; Read, R. W. J. Chem. Soc., Chem. Commun. 1979, 645-647. (b) Barrett, A. G. M.; Read, R. W.; Barton, D. H. R. J. Chem. Soc., Perkin Trans. 1 1980, 2191-2195. (c) Severengiz, T.; du Mont, W. W. J. Chem. Soc., Chem. Commun. 1987, 820-821.

(3) For telluroamides: Lerstrup, K. A.; Henriksen, L. J. Chem. Soc., Chem. Commun. 1979, 1102-1103.

(4) For telluroketenes: (a) Bender, S. L.; Haley, N. F.; Luss, H. R. Tetrahedron Lett. 1981, 22, 1495-1496. (b) Lakshmikantham, M. V.; Cava, M. P.; Albeck, M.; Engman, L.; Carroll, P. Ibid. 1981, 22, 4199-4200. (c) Lakshmikantham, M. V.; Cava, M. P.; Albeck, M.; Engman, L.; Bergman, J.; Wudl, F. J. Chem. Soc., Chem. Commun. 1981, 828-829.

(5) For metal complexes: (a) Lappert, M. F.; Martin, T. R.; McLaughlin, G. M. J. Chem. Soc., Chem. Commun. 1980, 635-637. (b) Fischer, H.; Zeuner, S. J. Organomet. Chem. 1983, 252, C63-C65. (c) Fischer, H.; Gerbing, U. Ibid. 1986, 299, C7-C10. (d) Fischer, H.; Pashalidis, I. Ibid. 1988, 348, C1-C4. (e) Headford, C. E. L.; Roper, W. R. Ibid. 1983, 244, C53-C56. (f) Hill, A. F.; Roper, W. R.; Waters, J. M.; Wright, A. H. J. Am.

Chem. *Soc*. 1983, *105*, 5939-5940. (g) Herrmann, W. A.; Weichmann, J.; Serrano, R.; Blechschmitt, K.; Pfisterer, H.; Ziegler M. L. *Angew*. *Chem*., *Int*. *Ed*. *Engl*. 1983, *22*, 314-315. (h) Paul, W.; Werner, H. *Ibid*. 1983, *22*, 316-317. (i) Wolf, J.; Zolk, R.; Schubert, U.; Werner, H. *J*. *Organomet*. *Chem*. 1988, *340*, 161-178.

(6) (a) Segi, M.; Nakajima, T.; Suga, S.; Murai, S.; Ryu, I.; Ogawa, A.; Sonoda, N. *J*. *Am*. *Chem*. *Soc*. 1988, *110*, 1976-1978. (b) Segi, M.; Takahashi, M.; Nakajima, T.; Suga, S.; Murai, S.; Sonoda, N. *Tetrahedron* *Lett*. 1988, *29*, 6965-6968.

(7) Segi, M.; Koyama, T.; Nakajima, T.; Suga, S.; Murai, S.; Sonoda, N. *Tetrahedron* *Lett*. 1989, *30*, 2095-2098.

(8) Erker, G.; Hock, R. *Angew*. *Chem*., *Int*. *Ed*. *Engl*. 1989, *28*, 179-180.

(9) Detty, M. R.; Seidler, M. D. *J*. *Org*. *Chem*. 1982, *47*, 1354-1356.

Conclusion

The aim of the present research was to develop general and convenient methods for generation of reactive compounds involving carbon-chalcogen multiple bonds. The important results mentioned in each chapter of this thesis are summarized as follows.

In chapter 1, a simple and convenient synthesis of selenoaldehydes via base-catalyzed reaction of aldehydes with bis(trimethylsilyl) selenide, which takes advantage of the large affinity of silicon to oxygen atom, has been described. The reaction was carried out in the presence of cyclopentadiene to give the Diels-Alder adducts of the corresponding selenoaldehydes and the diene. A catalytic cycle was illustrated for the present selenoaldehyde formation. Further, intramolecular trapping of selenoaldehydes offered a new entry to selenium containing carbocycles. It has been also revealed that the use of hexamethylcyclotrisilaselenane as a selenating reagent leads effectively to the successful trapping of selenoaldehydes by an acyclic 1,3-diene. Furthermore, as a synthetic application of this base-catalyzed reaction, various unsymmetrical selenium compounds were prepared by a one-pot operation using bis(trimethylsilyl) selenide.

In chapter 2, a new method for the direct conversion of ketones to selenoketones, which can be trapped as Diels-Alder adducts, using a novel selenating reagent, bis(dimethylaluminum) selenide that was prepared in situ via transmetallation reaction of bis(tributyltin) selenide with trimethylaluminum, has been described. The cycloaddition of selenoketones with a 1,3-diene proceeded effectively to give the cycloadducts in good yields, occasionally with a high regioselectivity.

Chapter 3 has described the synthesis of thioaldehydes using bis(trimethylsilyl) sulfide under the base-catalyzed condition and their cycloaddition reaction and Wittig type reaction. A variety of thioaldehyde cycloadducts were obtained in high yields. Wittig reaction of aromatic thioaldehydes with a phosphonium ylide proceeded to yield the corresponding olefins with the trans preference. It has been further apparent that an aldehyde is converted into a precursor of thioaldehyde by the reaction with bis(trimethylsilyl) sulfide in the absence of a trapping reagent under the base condition.

In chapter 4, the stereochemistry of thioketone cycloaddtion with 1,3-diene has been described. Diels-Alder reaction of aromatic thioketones gave "meta" type adducts as the predominant regioisomer, whereas aliphatic substituents reversed the regiochemistry to give a predominant "ortho-para" isomer.

In chapter 5, the first general method for the generation of both telluroaldehydes and telluroketones has been described.

The reaction of aldehydes with bis(dimethylaluminum) telluride in the presence of 2,3-dimethyl-1,3-butadiene in refluxing dioxane afforded the Diels-Alder adducts of the corresponding telluroaldehydes and the diene in satisfactory yields.

Characteristic feature of these reactions are summarized as follows.

(i) direct conversion of carbonyl compounds to chalcogeno-carbonyl compounds

(ii) a new entry to chalcogen containing heterocycles

(iii) applicability to wide substrates

(iv) simplicity of experimental procedures

Thus, general and convenient method for the construction of carbon-chalcogen double bonds, based on the large affinity of silicon and aluminum to oxygen atom, was established by the present research. It becomes possible to study the chemistry of reactive compounds involving carbon-chalcogen double bonds.

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