A Novel Strategy for Cyclobutane Formation. Fine Tuning of Cyclobutanation vs Cyclopropanation

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The reactions of (*E*)-1-(phenylseleno)-2-(trimethylsilyl)ethene (**1a**) and (*E*)-1-(phenylseleno)-2-(triethylsilyl)ethene (**1b**) with dimethyl 1,1-dicyanoethene-2,2-dicarboxylate (**2**) in the presence of $SnCl_4$ in CH_2Cl_2 at −78 °C for 1 h exclusively afforded [2 + 2] cycloadducts **3a** and **3b** in 71% and 78% yields, respectively. The exclusive [2 + 2] selectivity in the reaction of **1** with **2** in the presence of $SnCl_4$ is explained by destabilization of the proposed selenium-bridged intermediate that would lead to the [2 + 1] adduct by the presence of the two electron-withdrawing cyano groups. The reaction of **1a** with **2** at 0 °C to room temperature in the presence of $ZnBr_2$ gave a regioisomeric [2 + 2] cycloadduct **7a** in low yield along with a corresponding desilylated cyclobutane **8** as the major product in moderate to good yield. The origin of the Lewis acid dependence of the regioselectivity was deduced from a theoretical comparison of stability of Lewis acid complexes.

Introduction

New synthetic technologies based upon 1,2-silicon migration processes are developing into powerful methods for stereoselective synthesis of cycloalkanes and heterocycles.[1] However, a deeper understanding of the factors that control 1,2-silicon migration vs nonmigration is required to facilitate further development of the synthetic potential and also from the standpoint of mechanistic interest. In this context, cyclopentane formation (1,2-silicon migration) vs cyclobutane formation (nonmigration) in the Lewis acid-promoted [3 + 2] and [2 + 2] cycloaddition reactions of allylsilanes and α,β-unsaturated carbonyl compounds has been studied in some detail.[2] Furthermore, the Lewis acid-promoted reactions of allylsilanes and carbonyl groups to yield tetrahydrofurans (1,2-silicon migration) and oxetanes (nonmigration) have also been reported.[3] However, a rationale for systematically controlling migration or nonmigration selectivity remains to be discovered.

Recently, we have described a number of examples of a novel [2 + 1] cycloaddition reaction leading to cyclopropanes by the reaction of (*E*)-1-(phenylseleno)-2-silylethenes (**1**) with electrophilic olefins in the presence of Lewis acids, involving an unprecedented selenium-mediated 1,2-silicon migration.[4] During the course of these earlier investigations, we discovered a competitive cyclopropane vs cyclobutane formation in the reaction of **1** and methylenemalonate esters.[4c] However, so far in our investigations, no cyclobutane was produced exclusively in high yield; the few examples of cyclobutane formation seemed to result predominately from steric factors.[4c]

As part of further efforts to understand the criteria in control of 1,2-silicon migration vs nonmigration, we have now investigated the reaction of 1-(phenylseleno)-2-silylethenes **1** with dimethyl 1,1-dicyanoethene-2,2-dicarboxylate (**2**)[5] in the presence of Lewis acids and found that exclusive and efficient [2 + 2] cycloaddition reactions occurred. In this paper, we describe the $SnCl_4$-promoted [2 + 2] cycloaddition reactions of 1-seleno-2-silylethenes **1** with the highly electrophilic olefin **2** and the Lewis acid dependence of the regioselectivity in the [2 + 2] cycloaddition of **1** with **2**.

Results and Discussion

A. $SnCl_4$-Promoted [2 + 2] Cycloaddition of 1 with 2. The reactions between (*E*)-1-(phenylseleno)-2-(trimethylsilyl)ethene (**1a**) or (*E*)-1-(phenylseleno)-2-(triethylsilyl)ethene (**1b**) and **2** were carried out in the presence of $SnCl_4$. To a solution of **1a** or **1b** (1.0 equiv) in dichloromethane was added $SnCl_4$ (1.5 equiv), followed by dimethyl 2,2-dicyanoethene-1,1-dicarboxylate (**2**) (1.3 equiv) at −78 °C. The mixture was stirred at −78 °C for 1 h. The reaction mixture was quenched by triethylamine (2.3 equiv) to give [2 + 2] cycloadducts **3a** and **3b** as single products in 71% and 78% yields, respectively (eq 1). This $SnCl_4$-promoted cyclobutane formation is in contrast with the cyclopropane formation in our previous

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(3) (a) Akiyama, T.; Kirino, M. *Chem. Lett.* **1995**, 723. (b) Akiyama, T.; Yamanaka, M. *Synlett* **1996**, 1095.

(4) (a) Yamazaki, S.; Tanaka, M.; Yamaguchi, A.; Yamabe, S. *J. Am. Chem. Soc.* **1994**, *116*, 2356. (b) Yamazaki, S.; Katoh, S.; Yamabe, S. *J. Org. Chem.* **1992**, *57*, 4. (c) Yamazaki, S.; Tanaka, M.; Inoue, T.; Morimoto, N.; Kumagai, H. *J. Org. Chem.* **1995**, *60*, 6546. (d) Yamazaki, S.; Tanaka, M.; Yamabe, S. *J. Org. Chem.* **1996**, *61*, 4046. (e) Yamazaki, S.; Kumagai, H.; Takada, T.; Yamabe, S.; Yamamoto, K. *J. Org. Chem.* **1997**, *62*, 2968.

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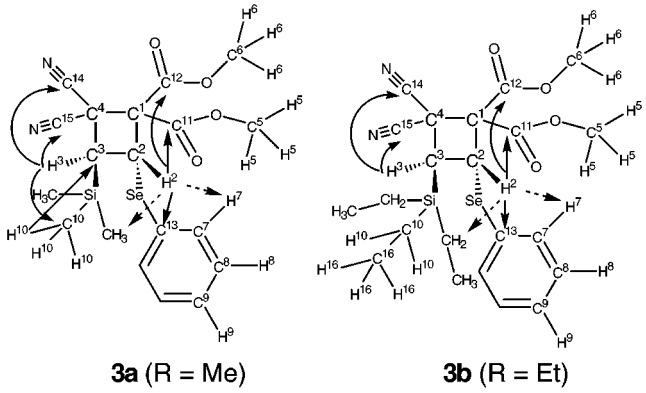
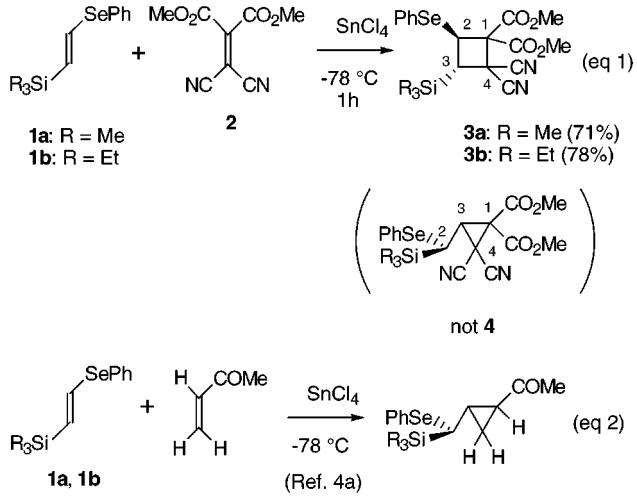


Figure 1. Selected ^{1}H, ^{13}C HMBC correlations (continuous arrows) and NOEs (dashed arrows) observed for **3a**,**b**. The atom numbering used in the Experimental Section is also indicated.

work (eq 2).[4a] The regio- and stereochemistry of the cyclobutane products was fully elucidated by HMBC and NOESY spectra (Figure 1). The observed HMBC correlations of **3** are in agreement with the cyclobutane structure, not the cyclopropane structure **4**. For example, if the structure were cyclopropane **4**, H^3 should have HMBC correlation with both *C*O_2Me and *C*N. However, only HMBC correlations between H^3*C*N (C^{14}, C^{15}) and H^2*C*O_2Me (C,[11] C^{12}) were observed. The HMBC correlations also determined the regiochemistry of **3**.



B. A Theoretical Investigation of [2 + 2] vs [2 + 1] Selectivity. To explain this exclusive [2 + 2] selectivity, and as an aid to further design of suitable substrates, potential reaction intermediates were considered in detail. The mechanism of the [2 + 2] cycloaddition process is suggested as illustrated in Scheme 1, i.e., similar to that previously reported.[4a] The nucleophilic vinyl selenide **1** attacks the electrophilic olefin **2** activated by $SnCl_4$ via a Se- - -C=O secondary orbital interaction to give a zwitterion intermediate **A**. The secondary orbital interaction is presumed by the largely localized HOMO at Se (vide post, Scheme 4) and the previous results of the stereochemistry of [2 + 2] cycloaddition of vinyl selenides and [2 + 1] cycloaddition of **1**.[4,6] The

Scheme 1

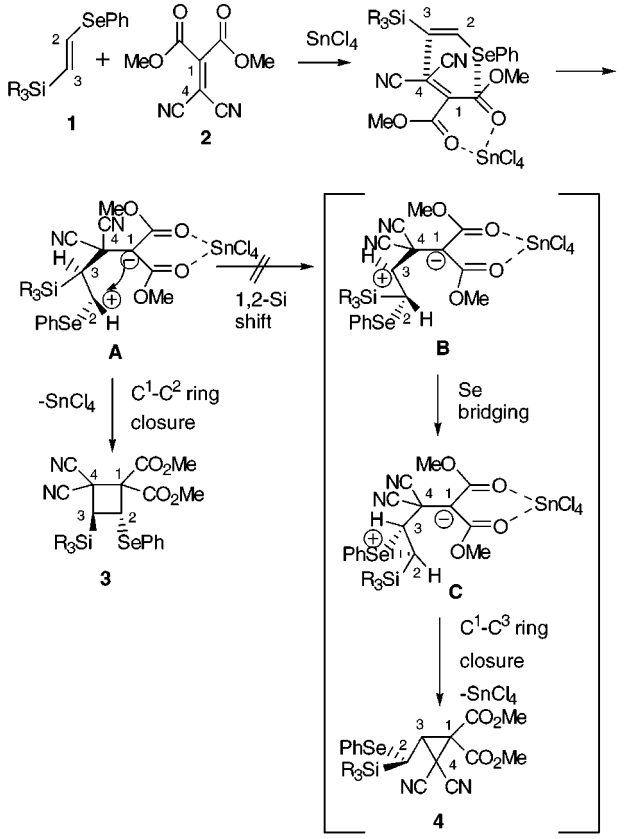


Table 1. Relative Energy of Model Compounds Calculated by the LANL1DZ Method

	substituent		models [relative energy, positive less stable (kcal/mol)]		
i	X^1	X^2			
1	CN	CN	**a**$_1$ [0]	**b**$_1$[a]	**c**$_1$ [+1.6]
2	CN	H	**a**$_2$ [0]	**b**$_2$ [+6.0]	**c**$_2$ [−1.3]
3	CHO	H	**a**$_3$ [0]	**b**$_3$ [+3.1]	**c**$_3$ [−2.1]
4[b]	H	H	**a**$_4$ [0]	**b**$_4$ [+1.3]	**c**$_4$ [−3.0]

[a] Structure **b**$_1$ converged to structure **a**$_1$. [b] See ref 4a.

coordination site of $SnCl_4$ in **2** is assumed to be the ester−carbonyl oxygen atoms in a bidentate arrangement as previously reported. Although the coordination site will be discussed in detail in Section C, the regiochemistry of the product **3** is in agreement with the oxygen coordination of $SnCl_4$. Ring closure of **A** gives a cyclobutane **3**. Alternatively, **A** could undergo rearrangement (1,2-silicon shift) to give a β-silicon-stabilized intermediate **B**. The intermediate **B** would be transformed to the selenium-bridged intermediate **C**, if **C** is more stable than **A**. Ring closure by internal nucleophilic attack at C^3 by C^1 in the intermediate **C** would give the cyclopropane **4**.

To understand the reasons why the process **A** → **B** → **C** → **4** does not occur, the stabilities of these intermediates (**A**−**C**) were compared by ab initio calculations. Scheme 2 illustrates cation models **a**$_1$, **b**$_1$, and **c**$_1$ (X^1 = X^2 = CN) corresponding to **A**−**C**. **a**$_1$ is an α-selenium- and β-silicon-stabilized cation. **b**$_1$ is a β-stabilized cation, and **c**$_1$ is a selenium-bridged one. In addition, the models **a**$_2$, **b**$_2$, and **c**$_2$ (X^1 = CN, X^2 = H and **a**$_3$, **b**$_3$, and **c**$_3$ (X^1 = CHO, X^2 = H) were also calculated. The models **a**$_2$, **b**$_2$, and **c**$_2$ are for the reaction of diethyl 2-cyanoethene-1,1-dicarboxylate (**5**) with **1**. The reaction of **5** with **1** in the presence of Lewis acid gave a mixture of [2 + 1] and [2 + 2] cycloadducts, but only in low yield.[4e] The models

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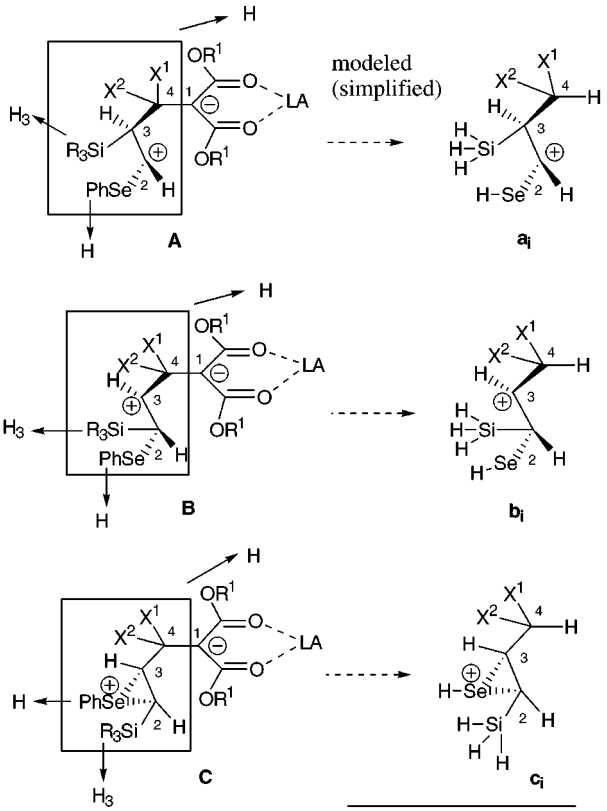
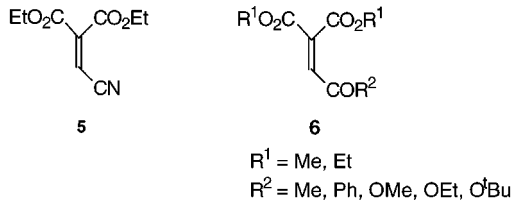
Scheme 2



i	X^1	X^2
1	CN	CN
2	CN	H
3	CHO	H
4	H	H

Model intermediates excluding the diester group coordinated by a Lewis acid (LA).

$\mathbf{a_3}$, $\mathbf{b_3}$, and $\mathbf{c_3}$ are for the reactions of tricarbonyl-substituted olefins **6** with **1** under Lewis acid-mediated conditions, which exclusively lead to cyclopropanes.[4e]



The geometry optimizations for the models $\mathbf{a_i}$, $\mathbf{b_i}$, and $\mathbf{c_i}$ were performed by using the LANL1DZ basis set.[7] GAUSSIAN 94 was used for ab initio calculations.[8] The relative energies are summarized in Table 1 together with those of the models $\mathbf{a_4}$, $\mathbf{b_4}$, and $\mathbf{c_4}$, which were calculated previously by the same method.[4a] The optimized geometries of $\mathbf{a_1}$ and $\mathbf{c_1}$ are shown in Figure 2. The structure of α-selenium and β-silicon-stabilized cation $\mathbf{a_1}$ was determined as an open form.[9] The structure of $\mathbf{b_1}$ converged to the structure $\mathbf{a_1}$. Table 1 for these model compounds clearly shows that the relative stability of the

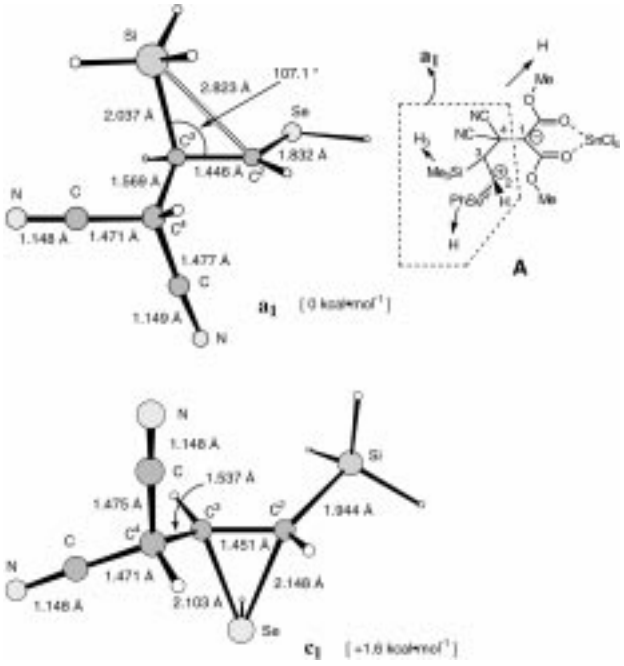


Figure 2. Ab initio RHF/LANL1DZ-optimized geometries of cation models $\mathbf{a_1}$ and $\mathbf{c_1}$. The modeling of **A** → $\mathbf{a_1}$ is exemplified. Energies in square brackets are taken from Table 1 and are relative (positive values, less stable).

β-silicon cation $\mathbf{b_i}$ and the selenium-bridged cation $\mathbf{c_i}$ compared to the α-selenium cation $\mathbf{a_1}$ decreases with increasing electron-withdrawing groups ($i = 4 \rightarrow 3 \rightarrow 2 \rightarrow 1$). The model $\mathbf{c_1}$ for the selenium-bridged intermediate **C** is less stable than model $\mathbf{a_1}$ for the α-selenium cation intermediate **A**. These results can be explained by destabilization of the proposed β-silicon cation intermediate **B** and selenium-bridged intermediate **C** by the two electron-withdrawing cyano groups. Furthermore, ab initio RHF/LANL1DZ geometry optimizations of the zwitterion models $\mathbf{a_5}$ for **A** and $\mathbf{c_5}$ for **C** were carried out. The obtained structures are shown in Figure 3. The model $\mathbf{c_5}$ is 1.1 kcal/mol less stable than the model $\mathbf{a_5}$. This result also supports the notion that the selenium-bridged intermediate **C** is less stable than the α-selenium cation intermediate **A**. Thus, the exclusive [2 + 2] selectivity in the reaction of **1** with **2** in the presence of $SnCl_4$ is rationalized in terms of the electronically unstable intermediate **C**. In other words, to obtain cyclopropanes that have larger ring strain than the

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(8) Frisch, M. J.; Trucks, G. W.; Schlegel, H. B.; Gill, P. M. W.; Johnson, B. G.; Robb, M. A.; Cheeseman, J. R.; Keith, T.; Petersson, G. A.; Montgomery, J. A.; Raghavachari, K.; Al-Laham, M. A.; Zakrzewski, V. G.; Ortiz, J. V.; Foresman, J. B.; Cioslowski, J.; Stefanov, B. B.; Nanayakkara, A.; Challacombe, M.; Peng, C. Y.; Ayala, P. Y.; Chen, W.; Wong, M. W.; Andres, J. L.; Replogle, E. S.; Gomperts, R.; Martin, R. L.; Fox, D. J.; Binkley, J. S.; Defrees, D. J.; Baker, J.; Stewart, J. J. P.; Head-Gordon, M.; Gonzalez, C.; Pople, J. A. Gaussian 94, Revision B.1, Gaussian, Inc., Pittsburgh, PA, 1995. MO calculations using Gaussian 94 were made on the CONVEX SPP1200/XA at the Information Processing Center (Nara University of Education). For $SnCl_4$-containing systems, the 6-311G basis set is not available in Gaussian 94.

(9) For theoretical studies of the β-silicon effect, see: (a) Wierschke, S. G.; Chandrasekhar, J.; Jorgensen, W. L. *J. Am. Chem. Soc.* **1985**, *107*, 1496. (b) Ibrahim, M. R.; Jorgensen, W. L. *J. Am. Chem. Soc.* **1989**, *111*, 819. For solvolysis studies of the β-silicon effect, see: (c) Lambert, J. B.; Wang, G.-t.; Finzel, R. B.; Teramura, D. H. *J. Am. Chem. Soc.* **1987**, *109*, 7838. (d) Lambert, J. B.; Chelius, E. C. *J. Am. Chem. Soc.* **1990**, *112*, 8120. (e) Lambert, J. B.; Emblidge, R. W.; Malany, S. *J. Am. Chem. Soc.* **1993**, *115*, 1317. See also, (f) Mayr, H.; Pock, R. *Tetrahedron* **1986**, *42*, 4211.

Table 2. [2 + 2] Cycloadditions of 1 and 2 with ZnX_2

entry	selenosilylethene	Lewis acid	reaction condns [*T* (°C) (time (h))]	**7** (yield (%))	**8** (yield (%))	**1a** (recovered yield (%))
1	**1a**	$ZnBr_2$	−30 (3), 0 (2)	5	49	46
2	**1a**	$ZnBr_2$	0 (5), rt (2)	12	66	22
3	**1a**	$ZnBr_2$	rt (5)	6	75	
4	**1a**	$ZnCl_2$	rt (5)		23	50
5	**1a**	ZnI_2	0 (5)	4	46	
6	**1b**	$ZnBr_2$	rt (5)	trace[a]	38	59
7	**1b**	ZnI_2	rt (5)		36	61
8	**1c**[b]	$ZnBr_2$	rt (15)		24	66
9	**1c**[b]	ZnI_2	rt (6)		10	85

[a] **7** (**7b**: R = Et) was not purified, and the structure was not fully determined. [b] The nucleophilic olefin **1c** has R = *i*-C_3H_7.

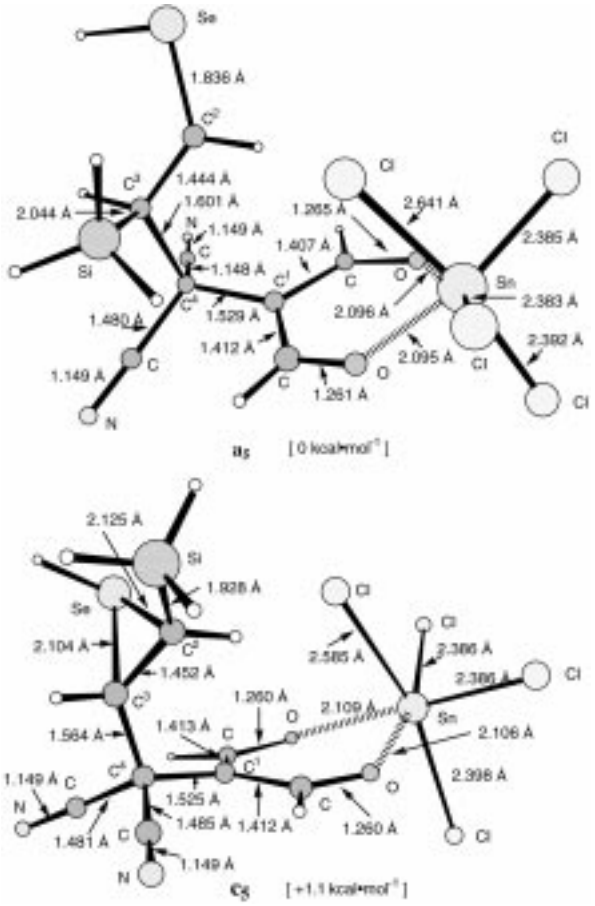
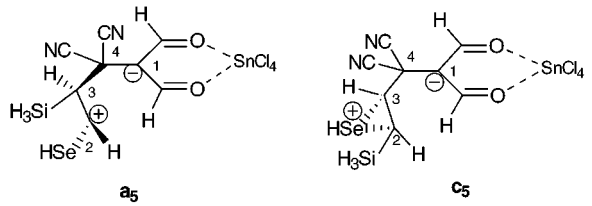


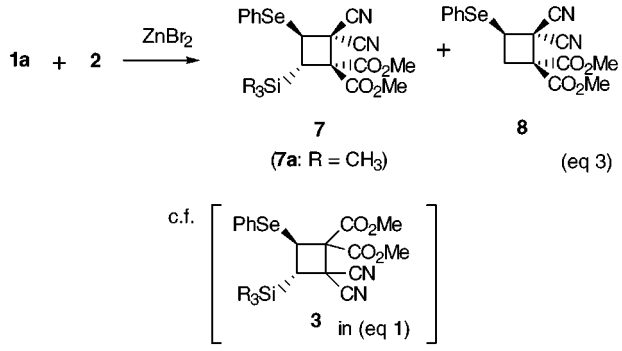
Figure 3. Ab initio RHF/LANL1DZ-optimized geometries of zwitterionic models $\mathbf{a_5}$ and $\mathbf{c_5}$. Energies in square brackets are relative (positive values, less stable).



corresponding cyclobutanes, the intrinsic stability of the intermediate **C** must be high.

The results from the model intermediates give significant insight into the design of suitable substrates for selective [2 + 1] or [2 + 2] Lewis acid-assisted cycloadditions with **1**. Thus, the present results suggest that moderately electrophilic olefins will lead to cyclopropanations, while highly electrophilic olefins are optimum for cyclobutanations.

C. ZnX_2-Promoted [2 + 2] Cycloadditions of 1 with 2. In addition to $SnCl_4$, various other Lewis acids were examined for the reaction between **1** and **2**. Use of $BF_3{\cdot}Et_2O$ and $AlCl_3$ gave highly complex mixtures. However, when zinc dihalides ZnX_2 were used as Lewis acids, an interesting switch of regioselectivity for [2 + 2] cycloadditions was observed (eq 3 and Table 2). Thus,



to a solution of **1a** (1 equiv) in CH_2Cl_2 was added $ZnBr_2$ (1.5 equiv), followed by **2** (1.3 equiv) at 0 °C; the mixture was then stirred at 0 °C for 5 h and at room temperature for 2 h. The reaction mixture was then quenched by triethylamine (2.3 equiv) to afford the regioisomeric [2 + 2] cycloadduct **7a** in 12% yield and the corresponding desilylated cyclobutane regioisomer **8** in 66% in yield. None of **3a** was observed. The reaction in the presence of $ZnBr_2$ under various temperature conditions gave **8** as the major product along with small amounts of **7a** (Table 2, entries 1−3).[10] Use of ZnI_2 and $ZnCl_2$ afforded **7a** and **8** similarly but in lower yields (Table 2, entries 4 and 5).

Reactions of **1b** and (*E*)-1-(phenylseleno)-2-(triisopropylsilyl)ethene (**1c**) with **2** in the presence of $ZnBr_2$ or ZnI_2 were also attempted for the purpose of suppression of desilylation (Table 2, entries 6−9). If the desilylation occurs by nucleophilic attack at silicon of the intermediate by a nucleophile such as X^- (Br^- or I^-), sterically demanding alkyl substituents on silicon may inhibit the attack and thus suppress desilylation. However, desilylated **8** was still the major product in both cases.

The regiochemistry for **7a** and **8** with regard to the PhSe and CN groups was syn and was opposite to that of **3**, which was the product from the reaction with $SnCl_4$. The regiochemistry of the cyclobutane products **7a** and

(10) When **3a** was treated with $ZnBr_2$ at 0 °C for 2 h, no isomeric cyclobutane **7a** was observed and **3a** was recovered. When **7a** was treated with $SnCl_4$ at −78 °C for 0.5 h, no cyclobutane **3a** was observed and **7a** was recovered. Treatment of **7a** with $ZnBr_2$ at room temperature for 5 h resulted in recovery of **7a**, and no desilylated **8** was produced. The control experiment showed that the trimethylsilyl group was not lost from **7a** to form **8** under the reaction conditions.

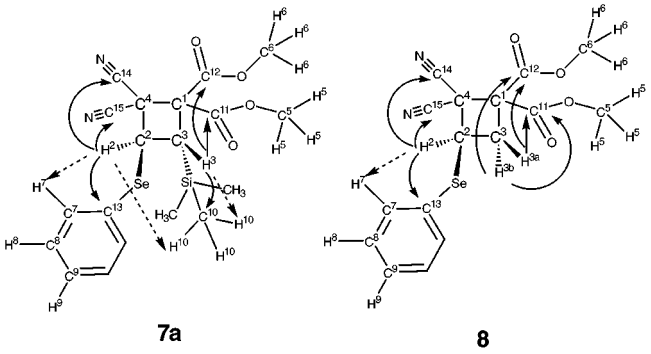
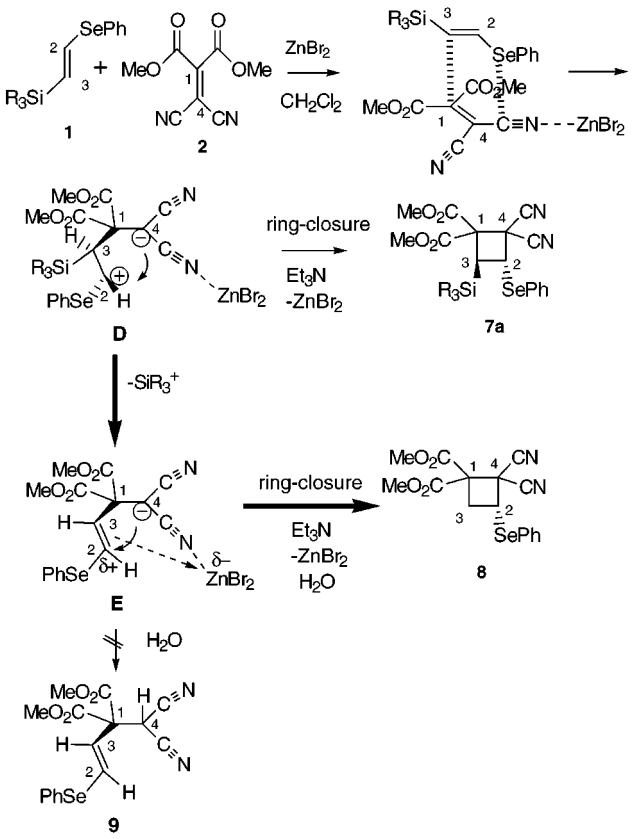


Figure 4. Selected ^1H, ^{13}C HMBC correlations (continuous arrows) and NOEs (dashed arrows) observed for **7a** and **8**. The atom numbering used in the Experimental Section is also indicated.

Scheme 3

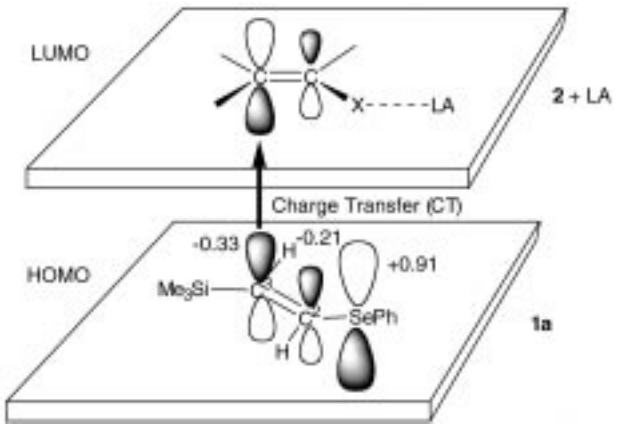


8 was fully elucidated by HMBC and NOESY spectra (Figure 4). The HMBC correlations of H^2-C^{14}, H^2−C^{15}, H^3−C^{11}, and H^3−C^{12} determined the regiochemistry of **7a** and **8**.

D. Origin of the Switched Regioselectivity. To explain the Lewis acid dependence of the regioselectivity in this [2 + 2] cycloaddition, the mechanism for the $ZnBr_2$-promoted reaction was depicted, as shown in Scheme 3. This is based on consideration of the control experiments described in ref 8 and is comparable with Scheme 1.

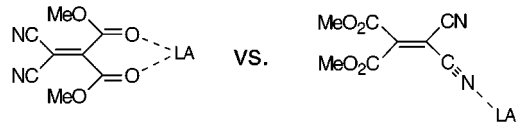
In the first addition step, frontier orbitals of **2**−Lewis acid complexes are LUMOs. Effective overlap of LUMOs with the HOMO of **1** determines the regiochemistry of the addition step to give a zwitterionic intermediate. When a Lewis acid is coordinated with one or two electron-withdrawing groups including heteroatoms (X),

Scheme 4

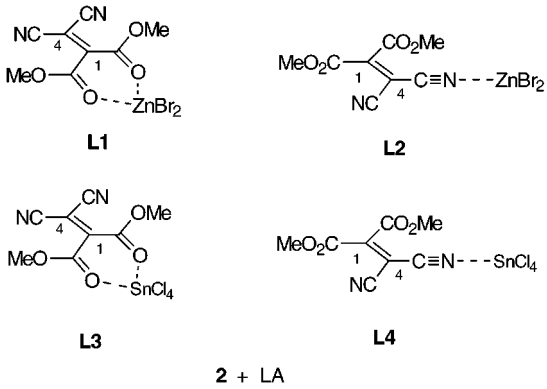


LUMO has a larger spatial extension at an olefin carbon distant from X. Frontier orbital coefficients of the HOMO of **1a** are shown in Scheme 4. These coefficients are derived from STO-3G//LANL2MB calculations.[7,8] In **1**, HOMO has a larger spatial extension at C_3 than at C_2.

The HOMO → LUMO charge transfer leads to the zwitterionic intermediate **A** (Scheme 1) or **D** (Scheme 3). That is, the difference of regiochemistry between **3** and **7** can be reasonably ascribed to that between **A** and **D** and, by inference, to the coordination sites of Lewis acids (vide infra).



Dependence on Lewis acids was examined in terms of Lewis acid −CN vs $-CO_2Me$ coordination patterns.[11] The stability of ZnO═C and ZnN≡C coordinations was compared by ab initio MO calculations. Total energies, including solvation (CH_2Cl_2) energy of the Lewis acid-coordinated **2**, **L1**−**L4**, were obtained by becke31yp/6-311G*//RHF/3-21G* for **L1**−**L2** and becke31yp/3-21G**//RHF/3-21G* calculations for **L3**−**L4**, respectively.[8]



Optimized geometries are displayed in Figure 5. The Sn−O coordinated **L3** is 20.4 kcal/mol more stable than

(11) ^1H and ^{13}C NMR spectroscopy studies were attempted for mixtures of **2** and Lewis acid (1:1) in CD_2Cl_2. The NMR was measured for **2**−$ZnBr_2$ at room temperature and for **2**−$SnCl_4$ at −50 °C to room temperature. However, the observed ^1H and ^{13}C NMR did not show significant differences in chemical shifts between free **2** and Lewis acid−**2** complexes. This result suggests that the equilibrium constants for complexation of Lewis acids and **2** are small.

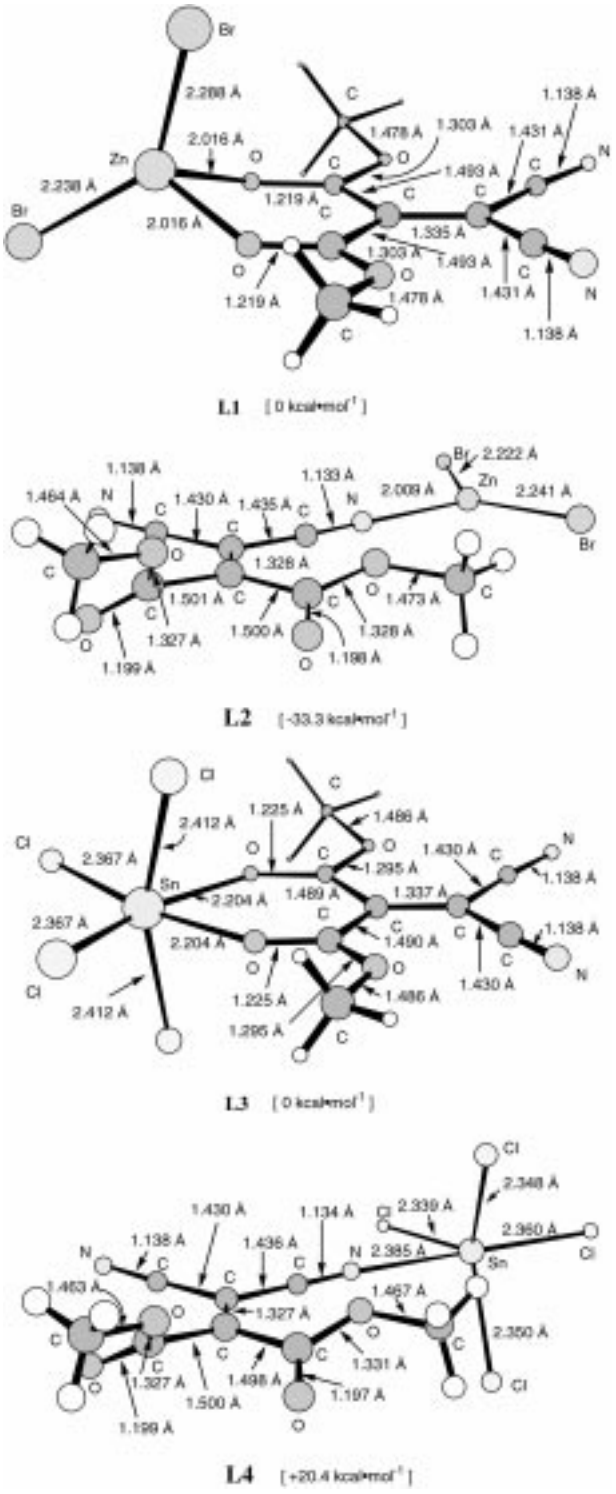
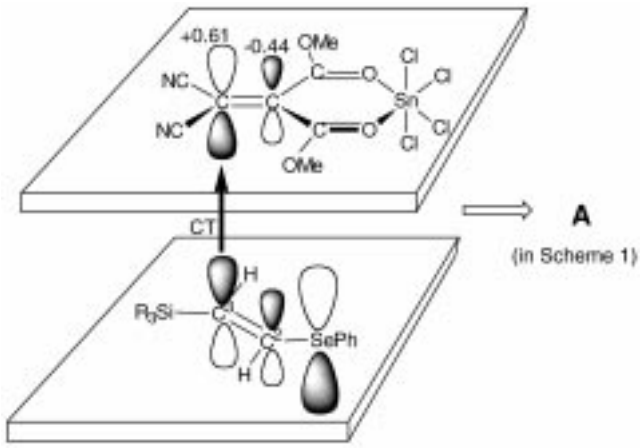


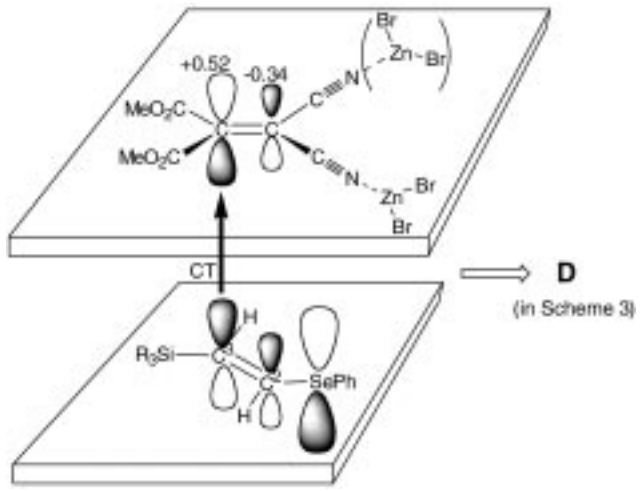
Figure 5. Ab initio RHF/3-21G*-optimized geometries of **L1**−**L4**. Energies in square brackets include solvation (CH_2Cl_2) energy by becke31yp/6-311G//RHF/3-21G* for **L1**−**L2** and becke31yp/3-21G**//RHF/3-21G* for **L3**−**L4** and relative to **L1** and **L3**, respectively (positive values, less stable).

the Sn−N-coordinated **L4**, respectively. In complete contrast, the Zn−N coordinated **L2** is 33.3 kcal/mol more stable than the Zn−O coordinated **L1**. This is because carbonyl oxygen atoms (hard bases) are more negatively charged than cyano nitrogen atoms (soft bases). Hard bases are directed by Coulombic attractions with hard acids. $SnCl_4$ is a hard acid, $Sn^{4+}(Cl^-)_4$ compared to $Zn^{2+}(Br^-)_2$ from the viewpoint of the charge of the metal

Scheme 5



Scheme 6

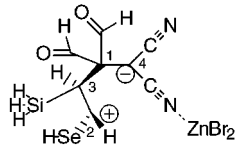


ion. The bidentate coordination model, **L3**, affords effective electrostatic stability, giving rise to the CT interaction shown in Scheme 5.

Soft bases (with high-energy HOMOs) are directed to charge donations toward soft acids. $ZnBr_2$ is a soft acid. By the single (or double) coordination of $ZnBr_2$ shown in Scheme 6, the regiochemistry opposite to **A** would result.

Although precise theoretical consideration of the solvent effect is infeasible for the present large systems, the different coordination pattern can be deduced from distances of coordination bonds in Figure 5. In **L1**, the bidentate Zn−O distances are 2.013 Å, while the Zn−N distance is 2.009 Å in **L2**. In **L3**, the bidentate Sn−O distances are 2.204 Å, while the Sn−N distance is 2.385 Å in **L4**. The distance trend is contrary between $SnCl_4$ and $ZnBr_2$ and also suggests the different regiochemistry.

The structure of the zwitterionic model **d** for the likely intermediate **D** was calculated by the LANL1DZ method



d

and is shown in Figure 6. Ring closure of the intermediate **D** gives cyclobutane **7a**, which is, however, a minor

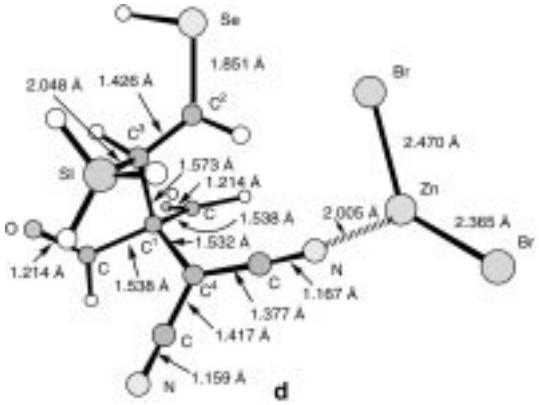
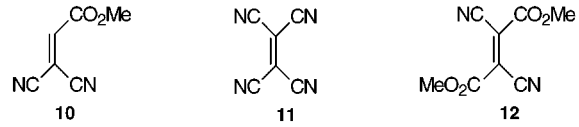


Figure 6. Ab initio RHF/LANL1DZ-optimized geometries of a zwitterionic model **d**.

pathway. The major pathway is desilylation of **D**. Structurally, the zwitterionic models $\mathbf{a_5}$ and **d** are similar; the Si−C^3 bond distance of $\mathbf{a_5}$ is 2.044 Å (Figure 3) and that of **d** is 2.048 Å (Figure 6). This similarity suggests that desilylation or preservation of a silyl group is not controlled by electronic properties. The higher reaction temperature may be the reason desilylation occurs in intermediate **D** and does not occur in intermediate **A** (in Scheme 1).

In reactions of allylsilanes, desilylation leads to noncyclized and allylated products.[1] In the previously reported reactions of **1**, use of strong Lewis acids, higher reaction temperatures, or quenching by water instead of triethylamine caused desilylation.[4] Desilylation leads to noncyclized and vinylated products, i.e., such compounds as **9** (in Scheme 3). A plausible mechanistic pathway leading to the formation of **8** can be formulated according to reported observations. For instance, a [2 + 2] cycloaddition reaction of (*E*)-1-(trimethylsilyl)-2-(isopropythio)-ethene with cyclohexenone in the presence of $BF_3{\cdot}Et_2O$ gives a desilylated cyclobutane.[12] This mechanism is involved in Scheme 3. Desilylation of **D** gives the vinylselenide intermediate **E**. In **E**, intramolecular activation of the olefin moiety by $ZnBr_2$ (shown by the dashed arrow in **E**, Scheme 3) allows intramolecular attack by the nucleophilic carbon C^4 to the positively polarized carbon C^2. Ring closure and subsequent protonation to C^3 leads to cyclobutane **8**.[13] However, since the process of desilylation is not clear at this stage, further investigation is underway. Without Lewis acid, no reaction occurred at room temperature in CH_2Cl_2 and also in CH_3CN.[14] Reactions of **1a** with electrophilic olefins **10**−**12**[5,15] in the presence of $SnCl_4$ or $ZnBr_2$ were also attempted. In most cases, **10**−**12** decomposed under the reaction conditions and no cycloadducts were obtained.



Concluding Remarks

We have shown exclusive [2 + 2] cycloaddition reactions of 1-seleno-2-silylethenes (**1**) with the highly electrophilic olefin, dimethyl 1,1-dicyanoethene-2,2-dicarboxylate (**2**), in the presence of Lewis acids. Exclusive [2 + 2] selectivity in the reaction of **1** with **2** in the presence of $SnCl_4$ was found. In addition, Lewis acid dependence of the regioselectivity in the [2 + 2] cycloaddition was observed. Thus, the reaction of **1a** in the presence of $ZnBr_2$ gave the regioisomeric [2 + 2] cycloadduct **7a** and the desilylated cyclobutane **8**.

The [2 + 2] cycloaddition reactions of electrophilic olefins and nucleophilic olefins have been extensively studied,[16] and recently, Lewis acid effects (existence or absence) have been systematically investigated.[14] Although [2 + 2] vs [4 + 2] cycloaddition competition has been observed previously,[15] Lewis acid dependence of regioselectivity has not hitherto been described. The phenylseleno-substituted cyclobutanes obtained here are considered to be potential precursors of cyclobutene derivatives, which are versatile synthetic intermediates.[17] In addition, wide synthetic application of the highly substituted [2 + 2] cycloadducts to biologically interesting cyclobutanes can be expected.[18] These studies are ongoing in our laboratories. It has been elucidated that silicon 1,2-migration vs nonmigration was controlled by stability of selenium-bridged intermediates by the presence or absence of electron-withdrawing cyano substituents. This finding will help further design of acceptor olefins for selective [2 + 1] or [2 + 2] cycloadditions of **1**.

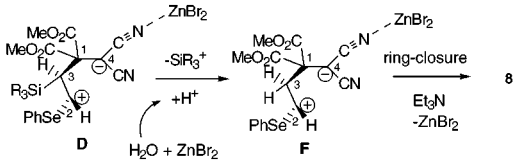
Experimental Section

General Methods. Melting points are uncorrected. IR spectra were recorded in the FT-mode. ^{1}H NMR spectra were recorded in $CDCl_3$ at 200, 500, or 600 MHz. ^{13}C NMR spectra were recorded in $CDCl_3$ at 50.1, 125.7, or 150.8 MHz. Chemical shifts are reported in ppm relative to Me_4Si or residual nondeuterated solvent. Mass spectra were recorded at an ionizing voltage of 70 eV by EI. All reactions were carried out under nitrogen atmosphere.

Dimethyl 4,4-Dicyano-2-(phenylseleno)-3-(trimethylsilyl)-2,3-*trans*-cyclobutane-1,1-dicarboxylate (3a). To a solution of **1a** (256 mg, 1.00 mmol) in dichloromethane (2.4 mL) was added $SnCl_4$ (0.173 mL, 391 mg, 1.50 mmol), followed by dimethyl 2,2-dicyanoethene-1,1-dicarboxylate (**2**) (252 mg, 1.30 mmol) at −78 °C. The mixture was stirred at −78 °C for

(12) Bonini, B. F.; Comes-Franchini, M.; Fochi, M.; Mazzanti, G.; Ricci, A. *Synlett* **1997**, 681.

(13) Formation of **8** can possibly be caused by protons generated from trace amounts of water in situ. Desilylation of **D** and subsequent protonation would give intermediate **F**, which leads to cyclobutane **8**.



(14) Reported regiochemistry of [2 + 2] cycloaddition of **2** and electron-rich olefins such as vinyl sulfide and vinyl ether *without* Lewis acid was also syn with regard to electron-donating groups (such as SR and OR) and CN groups. This is due to the coefficient of the LUMO at C^1 being larger than that at C^4 in **2** without Lewis acid. Srisiri, W.; Padias, B. A.; Hall, H. K., Jr. *J. Org. Chem.* **1994**, *59*, 5424.

(15) Hall, H. K., Jr.; Reineke, K. E.; Ried, J. H.; Sentman, R. C.; Miller, D. *J. Polym. Sci., Polym. Chem. Ed.* **1982**, *20*, 361.

(16) (a) Huisgen, R. *Acc. Chem. Res.* **1977**, *10*, 117 and 199. (b) Huisgen, R.; Brückner, R. *Tetrahedron Lett.* **1990**, *31*, 2553. (c) Brückner, R.; Huisgen, R. *Tetrahedron Lett.* **1990**, *31*, 2557 and 2561.

(17) For reviews, see: (a) Bellus, D.; Ernst, B. *Angew. Chem., Int. Ed. Engl.* **1988**, *27*, 797. (b) Fujiwara, T.; Takeda, T. *J. Synth. Org. Chem.* **1994**, *52*, 498. For the preparation of cyclobutenes, see: (c) Negishi, E.; Liu, F.; Choueiry, D.; Mohamud, M. M. *J. Org. Chem.* **1996**, *61*, 8325 and references therein.

(18) (a) Burgess, K.; Li, S.; Rebenspies, J. *Tetrahedron Lett.* **1997**, *38*, 1681. (b) Gourdel-Martin, M.-E.; Huet, F. *J. Org. Chem.* **1997**, *62*, 2166. (c) Hanrahan, J. R.; Taylor, P. C.; Errington, W. *J. Chem. Soc., Perkin Trans. 1* **1997**, 493.

1 h. The reaction mixture was quenched by triethylamine (0.32 mL, 233 mg, 2.3 mmol) and then saturated aqueous $NaHCO_3$. The mixture was extracted with dichloromethane, and the organic phase was washed with water, dried (Na_2SO_4), and evaporated in vacuo. The residue was purified by column chromatography over silica gel, eluting with hexanes−ether to give **3a** (320.7 mg, 71%) (R_f = 0.7 (hexane/ether = 1:2)) and unreacted **1a** (29 mg, 11%). **3a**: colorless crystals; mp 83 °C; ^{1}H NMR (600 MHz, $CDCl_3$) δ (ppm) 0.239 (s, 9H, H^{10}), 2.90 (d, J = 13.2 Hz, 1H, H^3), 3.85 (s, 3H, H^5), 3.97 (s, 3H, H^6), 4.32 (d, J = 13.2 Hz, 1H, H^2), 7.31−7.35 (m, 3H, $H^{8,9}$), 7.61−7.63 (m, 2H, H^7) (see the atom numbering in Figure 1); observed NOEs were H^2−H^3, H^2−H^7, H^2−H^{10}, H^3−H^{10}, H^7−H^8; ^{13}C NMR (150.8 MHz, $CDCl_3$) δ (ppm) −2.654 (q, J = 121 Hz, C^{10}), 33.28 (s, C^1), 39.06 (d, J = 133 Hz, C^3), 42.16 (dd, J = 156, 8.1 Hz, C^2), 53.59 (q, J = 149 Hz, C^5), 53.70 (q, J = 149 Hz, C^6), 68.02 (s, C^4), 112.5 (d, J = 6.3 Hz, C^{14}), 113.8 (d, J = 9.2 Hz, C^{15}), 128.6 (dt, J = 161, 7.3 Hz, C^9), 128.7 (s, C^{13}), 129.4 (dd, J = 161, 8.4 Hz, C^8), 134.4 (d, J = 162 Hz, C^7), 165.0 (s, C^{12}), 165.7 (s, C^{11}); observed HMBC correlations were H^2−C^1, H^2−C^3, H^2−C^4, H^2−C^{11}, H^2−C^{12}, H^2−C^{13}, H^3−C^1, H^3−C^2, H^3−C^4, H^3−C^{10}, H^3−C^{14}, H^3−C^{15}, H^5−C^{11}, H^6−C^{12}, H^7−C^9, H^9−C^7, H^9−C^8, H^{10}−C^3; ^{1}H and ^{13}C assignments were determined by NOESY, HMQC, and HMBC spectra; IR (neat) 2366, 1744 cm^{-1}; MS (EI) *m*/*z* (relative intensity) 450 (22), 391 (34), 234 (6.5), 189 (24), 157 (24), 73 (100); exact mass M^+ 450.0511 (calcd for $C_{19}H_{22}N_2O_4SeSi$ 450.0514).

Dimethyl 4,4-Dicyano-2-(phenylseleno)-3-(triethylsilyl)-2,3-*trans*-cyclobutane-1,1-dicarboxylate (3b). To a solution of **1b** (297 mg, 1.00 mmol) in dichloromethane (2.4 mL) was added $SnCl_4$ (0.173 mL, 391 mg, 1.50 mmol), followed by dimethyl 2,2-dicyanoethene-1,1-dicarboxylate (**2**) (252 mg, 1.30 mmol) at −78 °C. The mixture was stirred at −78 °C for 1 h. The reaction mixture was quenched by triethylamine (0.32 mL, 233 mg, 2.3 mmol) and then saturated aqueous $NaHCO_3$. The mixture was extracted with dichloromethane, and the organic phase was washed with water, dried (Na_2SO_4), and evaporated in vacuo. The residue was purified by column chromatography over silica gel, eluting with hexanes−ether to give **3b** (382 mg, 78%) (R_f = 0.7 (hexane/ether = 1:2)) and unreacted **1b** (23 mg, 7.7%). **3b**: colorless crystals; mp 76 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ (ppm) 0.733−0.860 (m, 6H, H^{10}), 1.02 (t, J = 7.9 Hz, 9H, H^{16}), 2.96 (d, J = 13.3 Hz, 1H, H^3), 3.87 (s, 3H, H^5), 3.97 (s, 3H, H^6), 4.40 (d, J = 13.3 Hz, 1H, H^2), 7.30−7.34 (m, 3H, $H^{8,9}$), 7.59−7.63 (m, 2H, H^7); observed NOEs were H^2−H^3, H^2−H^7, H^2−H^{10}, H^2−H^{16}, H^5−H^{16}; ^{13}C NMR (125.7 MHz, $CDCl_3$) δ (ppm) 2.533 (C^{10}), 7.313 (C^{16}), 33.52 (C^1), 36.81 (C^3), 42.27 (C^2), 53.63, 53.68 ($C^{5,6}$), 68.37 (C^4), 112.6 (C^{14}), 114.2 (C^{15}), 128.6 (C^9), 128.8 (C^{13}), 129.3 (C^8), 134.3 (C^7), 165.1 (C^{12}), 165.7 (C^{11}); observed HMBC correlations were H^2−C^3, H^2−C^4, H^2−C^{11}, H^2−C^{12}, H^2−C^{13}, H^3−C^1, H^3−C^2, H^3−C^{14}, H^3−C^{15}, H^5−C^{11}, H^6−C^{12}, H^7−C^9, H^9−C^8, H^{10}−C^{16}, H^{16}−C^{10}; IR (KBr) 2950, 2884, 2364, 2336, 1742 cm^{-1}; MS (EI) *m*/*z* (relative intensity) 492 (40), 433 (35), 305 (3.9), 269 (4.3), 247 (7.6), 194 (4.3), 157 (80), 115 (100); exact mass M^+ 492.0979 (calcd for $C_{22}H_{28}N_2O_4SeSi$ 492.0984). Anal. Calcd for $C_{22}H_{28}N_2O_4SeSi$: C, 53.76; H, 5.74; N, 5.70. Found: C, 53.71; H, 5.54; N, 5.90.

Reaction of 1a and 2 with $ZnBr_2$ (Entry 2 in Table 2). To a solution of **1a** (255 mg, 1.00 mmol) in dichloromethane (2.4 mL) was added $ZnBr_2$ (338 mg, 1.50 mmol), followed by dimethyl 2,2-dicyanoethene-1,1-dicarboxylate (**2**) (252 mg, 1.30 mmol) at 0 °C. The mixture was stirred at 0 °C for 5 h and then at room temperature for 2 h. The reaction mixture was quenched by triethylamine (0.32 mL, 233 mg, 2.3 mmol) and then saturated aqueous $NaHCO_3$. The mixture was extracted with dichloromethane, and the organic phase was washed with water, dried (Na_2SO_4), and evaporated in vacuo. The residue was purified by column chromatography over silica gel, eluting with hexanes−ether (1:2) to give **7a** (54 mg, 12%) (R_f = 0.7) and **8** (249 mg, 66%) (R_f = 0.5) and unreacted **1a** (55 mg, 22%).

7a: pale yellow oil; ^{1}H NMR (600 MHz, $CDCl_3$) δ (ppm) 0.113 (s, 9H, H^{10}), 2.70 (d, J = 13.5 Hz, 1H, H^3), 3.84 (s, 3H, H^5), 3.89 (s, 3H, H^6), 4.51 (d, J = 13.5 Hz, 1H, H^2), 7.35−7.39 (m, 3H, $H^{8,9}$), 7.65−7.66 (m, 2H, H^7); observed NOEs were H^2−H^3, H^2−H^5, H^2−H^7, H^2−H^{10}, H^3−H^6, H^3−H^{10}, H^7−H^8; ^{13}C NMR (150.8 MHz, $CDCl_3$) δ (ppm) −2.242 (q, J = 120 Hz, C^{10}), 37.53 (d, J = 125 Hz, C^3), 44.14 (dd, J = 161, 7.8 Hz, C^2), 44.86 (s, C^1), 53.70 (q, J = 149 Hz, C^6), 53.77 (q, J = 149 Hz, H^5), 60.80 (s, C^4), 111.7 (d, J = 4.7 Hz, C^{14}), 112.7 (d, J = 7.4 Hz, C^{15}), 127.2 (s, C^{13}), 129.2 (d, J = 162 Hz, C^9), 129.8 (d, J = 162, 8.4 Hz, C^8), 135.0 (J = 162 Hz, C^7), 166.2 (s, C^{12}), 166.4 (s, C^{11}); observed HMBC correlations were H^2−C^1, H^2−C^3, H^2−C^{13}, H^2−C^{14}, H^2−C^{15}, H^3−C^1, H^3−C^2, H^3−C^4, H^3−C^{10}, H^3−C^{11}, H^3−C^{12}, H^5−C^{11}, H^6−C^{12}, H^7−C^9, $H^{8,9}$−C^7, H^8−C^{13}, H^9−C^8, H^{10}−C^3; IR (neat) 2960, 2364, 2344, 1744 cm^{-1}; MS (EI) *m*/*z* (relative intensity) 450 (3.6), 391 (20), 345 (14), 314 (16), 277 (100), 189 (16), 157 (26), 84 (89); exact mass M^+ 450.0486 (calcd for $C_{19}H_{22}N_2O_4SeSi$ 450.0515).

8: pale yellow oil; ^{1}H NMR (600 MHz, $CDCl_3$) δ (ppm) 2.85 (dd, J = 12.8, 11.4 Hz, 1H, H^{3a}), 2.92 (dd, J = 12.8, 8.9 Hz, 1H, H^{3b}), 3.88 (s, 3H, H^5), 3.90 (s, 3H, H^6), 4.58 (dd, J = 11.4, 8.9 Hz, 1H, H^2), 7.34−7.37 (m, 2H, H^8), 7.38−7.41 (m, 1H, H^9), 7.64−7.66 (m, 2H, H^7); observed NOEs were H^2−H^{3b}, H^2−H^5, H^2−H^7, H^{3a}−H^{3b}, H^{3a}−H^6, H^{3b}−H^5, H^8−H^9; ^{13}C NMR (150.8 MHz, $CDCl_3$) δ (ppm) 34.00 (C^3), 40.48 (C^2), 42.21 (C^1), 53.91 (C^6), 54.47 (C^5), 57.97 (C^4), 111.7, 111.8 ($C^{14,15}$), 126.3 (C^{13}), 129.3 (C^8), 129.8 (C^9), 135.3 (C^7), 165.4 (C^{12}), 166.1 (C^{11}); observed HMBC correlations were H^2−C^1, H^2−C^3, H^2−C^4, H^2−C^{13}, H^2−C^{14}, H^2−C^{15}, H^{3a}−C^1, H^{3b}−C^1, H^{3a}−C^2, H^{3b}−C^2, H^{3a}−C^4, H^{3b}−C^4, H^{3a}−C^{11}, H^{3b}−C^{11}, H^{3a}−C^{12}, H^{3b}−C^{12}, H^{3b}−C^{14or15}, H^5−C^{11}, H^6−C^{12}, H^7−C^8, H^8−C^7, H^8−C^9, H^8−C^{13}, H^9−C^7; IR (neat) 2960, 2252, 1746 cm^{-1}; MS (EI) *m*/*z* (relative intensity) 378 (1.1), 335 (26), 303 (4.3), 291 (11), 275 (20), 229 (41), 217 (6.5), 159 (17); exact mass M^+ 378.0123 (calcd for $C_{16}H_{14}N_2O_4Se$ 378.0119). Anal. Calcd for $C_{16}H_{14}N_2O_4Se$: C, 50.94; H, 3.74; N, 7.43. Found: C, 50.79; H, 3.69; N, 7.14.

Supporting Information Available: Copies of 2D-NOESY and HMBC spectra for compounds **3a**,**b**, **7a**, and **8** (26 pages). This material is contained in libraries on microfiche, immediately follows this article in the microfilm version of the journal, and can be ordered from the ACS; see any current masthead page for ordering information.

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