

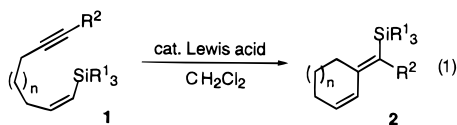
Lewis Acid-Catalyzed Stereoselective Intramolecular *trans*-Vinylsilylation of Unactivated Alkynes

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The intramolecular carbometalation reaction of alkynes is an attractive strategy not only for ring construction but also for formation of new organometallic compounds.¹ It has been known for many years that polar organometallics (R–M; M = Li, Mg, Zn, ...) undergo intramolecular carbometalation to alkynes.^{2–6} However, the carbometalation of alkynes with organosilicon compounds is not easy due to the lack of a method for activation of stable carbon–silicon bonds.⁷ Concerning polar organometallics, the carbometalation with allyl and alkyl reagents is more popular than that with vinyl and aryl reagents. To the best of our knowledge, there is no report on carbometalation of unactivated alkynes with vinylsilanes,^{8,9} although there are very few reports on the intramolecular carbometalation with vinylolithiums.¹⁰ We now report the first example for the vinylsilylation of unactivated alkynes; the Lewis acid-catalyzed reaction of the carbon tethered alkynyl vinylsilanes **1** gave (*E*)-cyclic dienyilsilanes **2** in good to high yields (eq 1).¹¹



The results are summarized in Table 1. The reaction of **1a**, having a tether chain of three methylene groups ($n = 1$), in the presence of 0.5 equiv of EtAlCl₂ gave the *trans*-carbosilylation product **2a** regio- and stereoselectively in 69% yield (entry 1).

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(7) For example, the mean bond dissociation energies $\bar{D}(M-R)$ of representative organometallics MR_n are as follows: Si–Et, 290 ± 25 kJ/mol; Li–Et, 209 kJ/mol; Zn–Et, 145 kJ/mol; Al–Et, 242 kJ/mol. See: Skinner, H. A. *Adv. Organomet. Chem.* **1964**, *2*, 49–114. Aylett, B. J. *Organometallic Compounds; The Main Group Elements, Part 2*; 1979; Vol. I.

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Table 1. Lewis Acid-Catalyzed Carbocyclization of **1**^a

entry no.	substrate 1		Lewis acid (equiv)	temp (°C)	yield of 2 (%) ^b
	<i>n</i>	R ¹ R ²			
1	1	Me H	1a EtAlCl ₂ (0.5)	–78	2a 69
2	1	Me H	1a AlCl ₃ (0.5)	–78	2a 67
3	1	Me H	1a AlBr ₃ (0.5)	–78	2a 56
4	1	Me H	1a EtAlCl ₂ (1.1)	–78	2a 61
5	1	Me H	1a EtAlCl ₂ (0.2)	–78	2a 92
6	1	Me H	1a EtAlCl ₂ (0.1)	–78 to 0	2a 49 ^c
7	1	Me H	1a AlCl ₃ (0.1)	–78 to –30	2a 84
8 ^d	1	Me H	1a EtAlCl ₂ (0.2)	–78	2a 91
9	1	Et H	1b EtAlCl ₂ (0.2)	–78 to –20	2b 85
10 ^e	1	Me C ₆ H ₁₃	1c EtAlCl ₂ (0.5)	rt	2c 31
11 ^e	1	Me SiMe ₃	1d EtAlCl ₂ (0.5)	rt	2d 85
12	2	Me H	1e AlCl ₃ (0.2)	–78 to –5	2e 89

^a Reactions were conducted in CH₂Cl₂ at the indicated temperature within 1 h, except for where otherwise mentioned. The reactions were quenched by adding excess amounts of Et₂NH and saturated aqueous NaHCO₃ solution at the reaction temperature. ^b Isolated yield. ^c The starting material **1a** was recovered in 23% yield. ^d Hexane was used as a solvent. ^e Reaction was conducted for 1 d.

We could not detect the formation of the stereo- (*cis*-addition product) and regioisomer (*endo*-cyclization product) of **2a**.¹² Other Lewis acids such as AlCl₃ and AlBr₃ were also effective for the present reaction (entries 2–3).¹³ Optimization experiments revealed that the use of 0.2 equiv of EtAlCl₂ gave the best result (entries 4–7). Besides CH₂Cl₂, hexane was a solvent suitable to the present vinylsilylation (entry 8). The cyclization of **1b** having the vinyltriethylsilyl moiety also proceeded smoothly to give **2b** in 85% yield (entry 9). The reaction of **1c** bearing hexyl-substituted internal alkyne gave the corresponding product in low yield (entry 10). On the other hand, the reaction of **1d** having trimethylsilyl-substituted internal alkyne gave the cyclization product **2d** in high yield (entry 11). Analogously, the cyclization of **1e**, having a tether chain of four methylene groups ($n = 2$), gave the seven-membered product **2e** in high yield (entry 12).

The preparation of **2a** is representative. To a solution of **1a** (0.5 mmol) in CH₂Cl₂ (5 mL) was added EtAlCl₂ (0.1 mmol, 1 M in hexane) at –78 °C. After the mixture was stirred for 5 min, excess amounts of diethylamine (0.5 mL) and a saturated aqueous solution of NaHCO₃ were added successively at the reaction temperature. The mixture was extracted with pentane three times. The combined extracts were dried (Na₂SO₄) and evaporated to leave the crude product, which was purified by column chromatography (silica gel, hexane eluent) to give **2a** (0.46 mmol) in 92% yield. The *trans*-vinylsilylation was unambiguously determined by the stereochemistry of the cyclization product **2a**; irradiation of the alkenyl proton attached to the carbon α to the trimethylsilyl group enhanced the signal of the alkenyl proton attached to the γ-carbon (6.4% NOE), whereas no enhancement of any signals of methylene protons on the carbocycle was observed.¹⁴

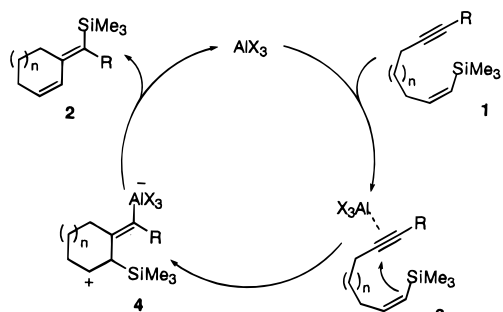
(11) It is well-known that the reactivity of vinylsilanes toward electrophiles is much lower than that of allylsilanes. Accordingly, it was rather surprising for us to discover that the vinylsilylation of **1** proceeded so smoothly in the presence of Lewis acids. See: (a) Colvin, E. W. *Silicon in Organic Synthesis*; Butterworth: London, 1981. (b) Weber, W. P. *Silicon Reagents for Organic Chemistry*; Springer-Verlag: Berlin, 1983. (c) Fleming, I.; Dunoguès, J.; Smithers, R. *Org. React. (N.Y.)* **1989**, *37*, 57–575.

(12) ¹H NMR signals due to very trace amounts of impurities were observed in the NMR spectra of **2a**; see Supporting Information. It was impossible to identify the structure of these impurities, although we attempted to separate them from **2a** by using GC and HPLC.

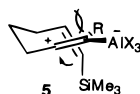
(13) Other Lewis acids such as ZrCl₄, HfCl₄, and B(C₆F₅)₃ did not catalyze the cyclization of **1a**.

(14) The stereostructures of products (**2c**, **2e**, **7b**, and **7c**) other than **2a** were determined similarly by NOE experiments. See Supporting Information.

Scheme 1



A plausible mechanism for the Lewis acid-catalyzed *trans*-vinylsilylation is shown in Scheme 1. The coordination of a Lewis acid to the triple bond of **1** would form π-complex **3**.^{15,16} The α-carbon of the vinylsilyl moiety would attack the electron-deficient triple bond from the side opposite to the Lewis acid to produce an aluminum ate complex **4** stereoselectively. The migration of the trimethylsilyl group to the aluminum center would afford **2** and regenerate the Lewis acid. A zwitterionic intermediate such as **5** may intervene in the step from **3** to **4**. Obviously, when



the vinylsilyl group approaches the electron-deficient carbon of the alkenylaluminum, a sterically demanding R group would hamper the approach of the vinylsilyl group (see **5**). This is the reason the reaction of **1c**, having hexyl-substituted internal alkyne (R = C₆H₁₃), was sluggish and the cyclization product was obtained in low yield (Table 1, entry 10). On the other hand, the smooth cyclization of **1d** can be accounted for by the well-known β-silyl effect: the carbocation β to the trimethylsilyl group is stabilized significantly.¹⁷ The *Z*-vinylsilylamine reacts with retention of configuration, which is the normal stereochemistry for the electrophilic substitution of a vinylsilylamine, whereas the *E*-isomer has to undergo inversion, which it is reluctant to do.¹⁸ Indeed, no cyclization product was obtained when the (*E*)-isomer of **1a** was treated with a catalytic amount of AlCl₃. Previously, we reported that the coexistence of chlorotrialkylsilane was essential for obtaining high chemical yields of the cyclization products in HfCl₄-catalyzed allylsilylation of alkynes.⁹ It is worth mentioning that the present reaction proceeded very well in the absence of chlorotrimethylsilane.

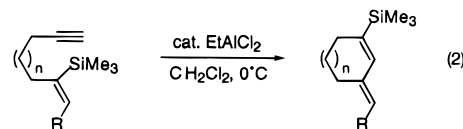
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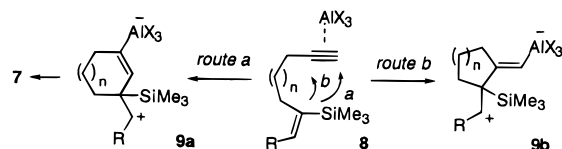
Since the intramolecular vinylsilylation of the unactivated alkynes **1** proceeded unexpectedly easily, we next examined the cyclization of differently substituted vinylsilylalkynes **6**. Although no cyclization product was obtained in the reaction of **6a**, this is normal for electrophilic attack on a vinylsilylalkyne of this type. However, the cyclizations of **6b** and **6c** took place in the presence of a catalytic amount of EtAlCl₂ and the *trans*-vinylsilylation products **7b** and **7c** were obtained, respectively (eq 2), because



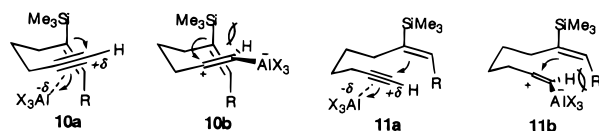
6a : n=1, R=H	7a : n=1, R=H	0%
b : n=1, R=C ₃ H ₇	b : n=1, R=C ₃ H ₇	90%
c : n=2, R=C ₃ H ₇	c : n=2, R=C ₃ H ₇	35%

the carbocation of **9a** is stabilized by the substituent R (**6b–c**, R = C₃H₇) (vide infra). Interestingly, these products were produced via an *endo*-mode cyclization in contrast to the reactions of **1**, which proceeded in an *exo*-mode fashion. These results can be accounted for by the following mechanistic rationale (Scheme 2). When the α-carbon of vinylsilylalkyne attacks the terminal

Scheme 2



acetylenic carbon of complex **8** (route a, *endo*-mode), which was formed from **6** and Lewis acid, no significant steric repulsion would be produced (**10a** and **11a**), although the terminal acetylenic carbon should be electronically deficient. In contrast, *exo*-mode cyclization (route b) proceeds via a vinylcation on the internal acetylenic carbon as shown in **10b** and **11b**. Serious steric repulsion between the vinylic proton and vinylsilylamine moiety would destabilize these intermediates. Accordingly, the *endo*-mode cyclization would take place to give **9a**, leading to **7** and AlX₃.



In conclusion, we have developed the first intramolecular *trans*-vinylsilylation of unactivated alkynes. The present reaction provides a new carbocyclization method for the preparation of the six- and seven-membered cyclic dienylysilylalkynes. Further studies to elucidate the mechanism of this reaction and to extend the scope of synthetic utility are in progress in our laboratory.

Supporting Information Available: Spectroscopic and analytical data for **2a–e** and **7b–c** (PDF). This material is available free of charge via the Internet at <http://pubs.acs.org>.

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