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Sakurai Reaction of 3,3-Bis(silyl) Silyl Enol Ethers with Acetals Involving Selective Desilylation of the Geminal Bis(silane). Concise Synthesis of Nematocidal Oxylipid

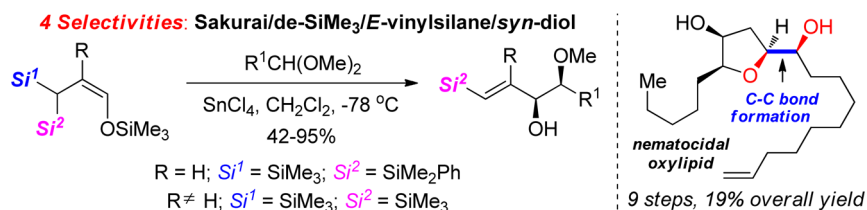
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ABSTRACT



3,3-Bis(silyl) silyl enol ethers have been shown to exhibit predominantly Sakurai reactivity, rather than Mukaiyama aldol reactivity, in their Lewis acid promoted reactions with acetals. Starting from a geminal bis(silyl) moiety consisting of two different silyl groups, such as SiMe₃ and SiMe₂Ph, the SiMe₃ is selectively eliminated to give monoprotected *E*-vinylsilyl diols with good to excellent *syn*-diastereoselectivity. This reaction also underpinned a synthesis of the nematocidal oxylipid from *Nothia anomala*, demonstrating the attractive bifunctionality of geminal bis(silanes).

Organosilanes¹ are extremely useful in organic synthesis. Organosilanes with diverse structural features usually possess quite different reactivities, and research into this diverse reactivity has led to many significant achievements in both the areas of synthetic methodology and natural product synthesis. Therefore, the discovery of structurally unique organosilanes could provide important breakthroughs in the development of novel reactions. With this goal in mind, we recently launched a series of studies on geminal bis(silanes) **1**^{2,3} that contain two bulky silyl groups

attached to a single carbon center (Scheme 1, left).⁴ Our recent work, however, has shown that these compounds exhibit unusual behavior that makes them particularly useful as bifunctional synthons,² suggesting that they can contribute to a much broader range of reactions than previously thought.

Among the various geminal bis(silanes) that have been described, 3,3-bis(silyl) silyl enol ethers of general structure **2** appear to be particularly interesting (Scheme 1, right).

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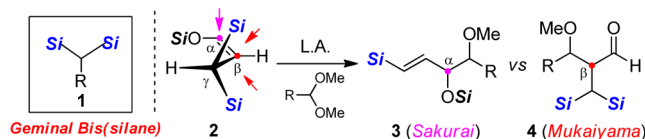
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Scheme 1. General Structure of Geminal Bis(silane) (left); Sakurai vs Mukaiyama Adol Reaction of 3,3-Bis(silyl) Silyl Enol Ether with Acetal (right)



In previous work, we proposed the most favorable conformation of **2^{2a}** is that which minimizes allylic strain and non-bonded interactions, and which also benefits from a double-hyperconjugation effect between the two C–Si bonds and the enol double bond. Since both the silyl enol ether and allyl bis(silane) groups in **2** share the same Z–C=C double bond, the compound was expected to participate in two competing pathways in a Lewis acid promoted reaction with an acetal. Such a reaction could either proceed by a Mukaiyama⁵ aldol pathway at the β -position to give aldehyde **4** or undergo umpolung⁶ and proceed by a Sakurai⁷ pathway at the α -position to give monoprotected diol **3**. Here we report detailed studies of this reaction and observe that up to four different selectivities can be achieved in a single transformation.

Table 1. Screening of Sakurai Reaction Conditions^a

entry	2	Si ¹	Si ²	R	L.A.	3 (% ^b /dr ^f)	4 (% ^b)
1	2a	SiMe ₃	SiMe ₃	SiMe ₃	TiCl ₄	3a (54/≥95:5)	4a (21)
2	2a	SiMe ₃	SiMe ₃	SiMe ₃	BF ₃ ·OEt ₂	3a (30/≥95:5)	4a (20)
3	2a	SiMe ₃	SiMe ₃	SiMe ₃	SnCl ₄	3a (70/≥95:5)	4a (23)
4	2b	SiMe ₃	SiMe ₃	SiEt ₃	SnCl ₄	3a (40/≥95:5)	4a (18)
5	2c	SiMe ₃	SiMe ₃	Me	SnCl ₄	3b (39/80:20)	4a (19)
6	2d	SiMe ₃	SiMe ₃	COPh	SnCl ₄	3c (41/70:30)	4a (0)
7	2e	SiMe ₂ t-Bu	SiMe ₂ t-Bu	SiMe ₃	SnCl ₄	3d (0)	4b (0)
8	2f	SiMe ₃	SiMe ₂ Ph	SiMe ₃	SnCl ₄	3e (80/≥95:5)	4c (10)

^a Reaction conditions: 0.15 mmol of **2**, 0.18 mmol of *p*-Cl-PhCH(OMe)₂, and 0.22 mmol of Lewis acid in CH₂Cl₂ (3.0 mL) at –78 °C for 30 min. ^b R = H in **3a** and **3e**. ^c The *E*-configuration was assigned based on ³J_{H–H} vinylic coupling constants ranging from 18 to 20 Hz in **3**. The *syn*-stereochemistry was determined by NOE experiments on the acetone of desilylated **3a**. ^d Stereochemistry was not determined. ^e Isolated yields after purification by silica gel column chromatography. ^f Ratios were determined by ¹H NMR spectroscopy.

The reaction was initially examined using global SiMe₃-substituted **2a** and *p*-Cl-PhCH(OMe)₂ in CH₂Cl₂ at –78 °C. SnCl₄ appeared to be a better Lewis acid than both TiCl₄ and BF₃·OEt₂ for leading the reaction predominantly along the Sakurai pathway (Table 1, entries 1–3).

With concomitant removal of the SiMe₃ group on oxygen, monoprotected *E*-*syn*-diol **3a** was generated in 70% yield and ≥95:5 *dr*, and Mukaiyama aldol product **4a** was produced in 23% yield. The substrate shows selectivity for Sakurai reactivity probably because the bulky bis(silyl) moiety shields both sides of the β -position in **2**, making the competitive Mukaiyama aldol reaction unfavorable. Switching the R group from SiMe₃ to the larger SiEt₃ or smaller Me group dramatically reduced the yield, and switching to Me also reduced the diastereoselectivity (entries 4 and 5). Switching R to an electron-withdrawing benzoyl group completely suppressed the Mukaiyama aldol pathway, but **3c** formed with only a moderate yield and diastereoselectivity (entry 6). More interesting results were obtained when we examined the effect of geminal bis(silane) on the reaction. When both Si¹ and Si² were an SiMe₂t-Bu group, neither the Sakurai nor Mukaiyama aldol reaction occurred (entry 7). This led us to hypothesize that if the geminal bis(silyl) moiety consisted of a SiMe₃ group and a bulkier SiMe₂t-Bu or SiMe₂Ph group, the more reactive SiMe₃ might be selectively eliminated. To the best of our knowledge, few studies have addressed this interesting selectivity issue.⁸ As expected, the reaction of **2f** provided **3e** in 80% yield, with only the SiMe₃ eliminated (entry 8). Moreover, the ratio of **3** to **4**, in this case, was higher than that in entry 1 due to increased hindrance around the β -position in **2f**. Thus, four different selectivities were realized in a single transformation: Sakurai over Mukaiyama aldol reaction, elimination of SiMe₃ over SiMe₂Ph, *E*- over *Z*-configuration, and *syn*- over *anti*-diastereoselectivity.

The scope of this reaction was then tested using **2f** and various acetals derived from aryl, alkyl, and alkynyl aldehydes. All reactions proceeded predominantly via the Sakurai pathway and gave the monoprotected *E*-*syn*-diol (\pm)-**3** in acceptable-to-good yields (Table 2), even though Mukaiyama aldol products were still obtained in some cases in yields around 10%. In all cases, the SiMe₃ was reliably eliminated, generating SiMe₂Ph-substituted *E*-vinylsilanes selectively. The diastereoselectivity was excellent in most reactions, except for the *dr* of 86:14 for the sterically less

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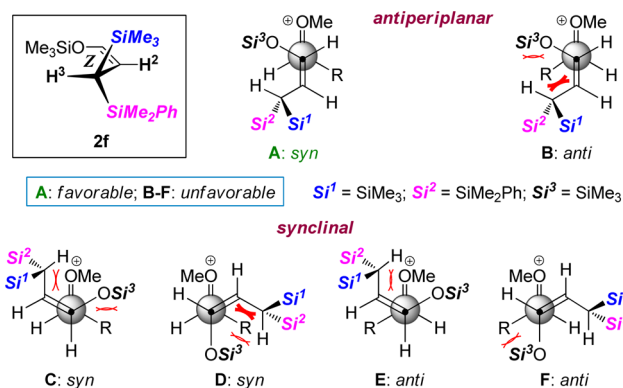
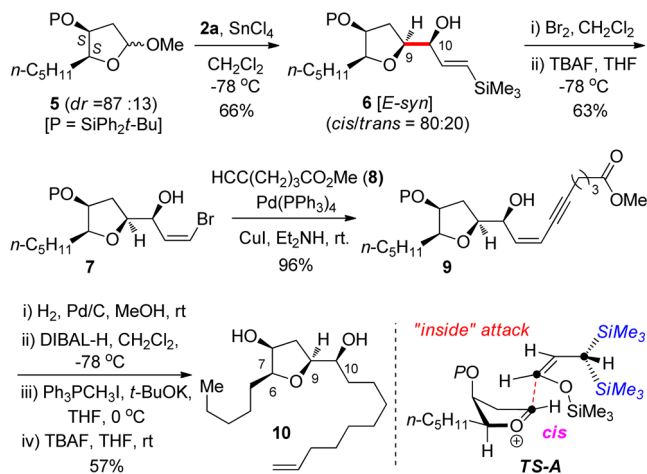
Table 2. Scope of Sakurai Reaction of **2f** with Acetals^a

entry	acetal	product	yield ^c	dr ^d
1 ^b	PhCH(OMe) ₂		63%	≥95:5
2 ^b	<i>p</i> -CO ₂ Me-PhCH(OMe) ₂		70%	≥95:5
3 ^b	<i>p</i> -F-PhCH(OMe) ₂		58%	≥95:5
4 ^b	<i>p</i> -Me-PhCH(OMe) ₂		65%	≥95:5
5 ^b	PhC ₂ H ₄ CH(OMe) ₂		56%	≥95:5
6 ^b	BnOC ₄ H ₉ CH(OMe) ₂		70%	≥95:5
7 ^b	BrCH ₂ CH(OMe) ₂		50%	90:10
8	<i>i</i> -PrCH ₂ CH(OMe) ₂		81%	≥95:5
9	Et ₃ SiC≡CCH(OMe) ₂		53%	86:14
10	<i>p</i> -Cl-PhCH(Obn) ₂		64%	≥95:5

^a Reaction conditions: 0.15 mmol of **2f**, 0.18 mmol of acetal, and 0.22 mmol of SnCl₄ in CH₂Cl₂ (3.0 mL) at –78 °C for 30 min. ^b Mukaiyama aldol products were observed in yields around 10%. ^c Isolated yields after purification by silica gel column chromatography. ^d Ratios were determined by ¹H NMR spectroscopy.

demanding diol **3n** (entry 9). This approach is also suitable for acetals derived from benzyl alcohol to provide **3o**, in which the benzyl group would be much easier to remove than the methyl group (entry 10).

We next examined reactions of various 3,3-bis(trimethylsilyl) silyl enol ethers bearing methyl, phenyl, or allyl substituents at the β-position (Table 3). In all cases, the additional steric hindrance at the β-position completely inhibited the

Scheme 2. Model Analysis to Explain the Observed *E*-*syn*-Selectivity during Sakurai Reaction of **2f** with Acetal**Scheme 3.** Synthesis of Nematocidal Oxylipid **10**

competitive Mukaiyama aldol reaction. Moreover, mono-protected *E*-*syn*-diol **3** was obtained as the major or only product in all cases, indicating that introduction of a β-substituent had no impact on stereoselectivity. Reaction of **2g** with a cyclic acetal provided an even more attractive result, given the widespread existence of substituted tetrahydropyrans in natural products (entry 3).⁹

The observed *E*-*syn*-selectivity can be rationalized using non-β-substituted **2f** to simplify the discussion (Scheme 2). The *E*-selectivity can be easily explained as a result of SiMe₃ elimination in the most favorable conformation of **2f**. Based on the classical antiperiplanar and synclinal orientations applied to S_{E'} additions of allylic silanes,^{1b,10} the “open” transition states A–F can be proposed, in which the C–SiMe₃ bond to be eliminated is positioned

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Table 3. Scope of Sakurai Reaction of β -Substituted 3,3-Bis(silyl) Silyl Enol Ethers **2** with Acetals^a

entry	2 (R ¹ , R)	acetal	product	yield ^c	dr ^d
1	2g (Me, Me)	<i>p</i> -Cl-PhCH(OMe) ₂	3p	95%	≥95:5
2	2g (Me, Me)	BnOC ₄ H ₉ CH(OMe) ₂	3q	67%	80:20
3	2g (Me, Me)		3r	80%	90:10
4	2h (Ph, Et)	<i>p</i> -Cl-PhCH(OMe) ₂	3s	66%	≥95:5
5	2i ^e (allyl, Et)	<i>p</i> -Cl-PhCH(OMe) ₂	3t	42%	≥95:5

^a Reaction conditions: 0.17 mmol of **2**, 0.21 mmol of acetal, and 0.26 mmol of SnCl₄ in CH₂Cl₂ (3.0 mL) at –78 °C for 30 min. ^b The *E*-configuration was assigned based on NOE experiments on **3p**. The *syn*-stereochemistry was determined by NOE experiments on the acetone of desilylated **3p**.

^c Isolated yields after purification by silica gel column chromatography.

^d Ratios were determined by ¹H NMR spectroscopy. ^e *Z/E* = 63:37.

anti to the C–C bond to be formed. While the observed stereochemical control may arise from a number of effects, our model assumes that the steric effect predominates. Based on this assumption, transition states **B** and **D** involving

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(12) Acetal **5** was prepared from the known (*S*, *S*)-lactone by two steps and in 85% overall yield. See Supporting Information for details.

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severe gauche interaction between bis(silyl) and R groups can be ruled out, as can transition states **C**, **E**, and **F** involving general gauche interactions between bis(silyl) and OMe groups, as well as between OSiMe₃ and R groups. The remaining transition state, antiperiplanar **A**, appears to be the most favorable for selective *syn*-addition.

We used this methodology to achieve a concise synthesis of nematocidal oxylipid **10** (Scheme 3), which was isolated from *Nothelia anomala* and has shown nematocidal activity comparable to that of commercially available nematocides.¹¹ The Sakurai reaction of **5**¹² with 2.0 equiv of **2a** proceeded smoothly and gave rise to the desired allylated product **6** in 66% yield, with complete *E-syn*-stereochemical control and a *cis/trans* ratio of 80:20.¹³ Thus, the C9/C10-*syn*-stereochemistry and the entirely *cis*-stereochemistry on the tetrahydrofuran ring was established in a single transformation. The resulting *E*-vinylsilane moiety in **6**, as the second functionality of geminal bis(silane), was then transformed into *Z*-vinyl bromide **7** in 63% yield.¹⁴ Vinyl bromide **7**, in turn, underwent Sonogashira coupling with terminal alkyne **8** to provide **9** in 96% yield. In this way, the long chain was efficiently incorporated on the right side in the target. The final steps of hydrogenation, reduction, Wittig olefination, and deprotection then furnished oxylipid **10** successfully.

To summarize, we have described a Lewis acid promoted reaction of 3,3-bis(silyl) silyl enol ethers with acetals, in which a predominant Sakurai reactivity rather than Mukaiyama aldol reactivity, as well as a selective desilylation of geminal bis(silane), was observed. This reaction also served as a key step in a concise synthesis of nematocidal oxylipid **10** from *Nothelia anomala*, demonstrating the attractive bifunctionality of geminal bis(silane). More extensive studies on other applications of this reaction are underway.

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Supporting Information Available. Experimental procedures and spectra data for products. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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The authors declare no competing financial interest.