JACS
JOURNAL OF THE AMERICAN CHEMICAL SOCIETY

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Oxidant-Controlled Stereoselectivity in the Pd-Catalyzed Allylic Oxidation of *cis*-Vinylsilanes

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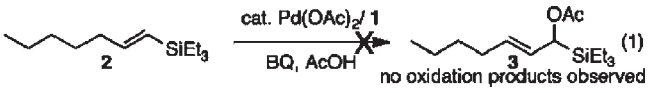
Supporting Information

ABSTRACT: The allylic oxidation of *cis*-vinylsilanes is reported. The reaction requires a low catalyst loading of $Pd(OAc)_2$ without the need for an external ligand. Interestingly, *trans*-vinylsilanes are unreactive, whereas allylic oxidations of *cis*-vinylsilanes proceed in good yields giving a single diastereo- and regioisomer of the branched allylic acetate *trans*-vinylsilane when benzoquinone is employed. The use of $PhI(OAc)_2$ as oxidant in place of benzoquinone provides the branched, *cis*-vinylsilane as the major product. Additionally, the first intramolecular allylic C−H etherifications of *cis*-vinylsilanes to give oxygen heterocycles are also described.

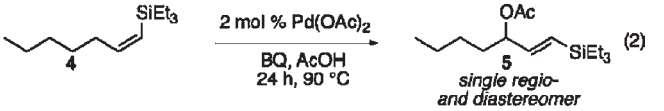
The renewed interest toward the discovery of catalysts for the selective allylic C−H oxidation of terminal olefins demonstrates the utility of the products in these reactions. Recent literature reports describe the selective allylic oxidation of terminal olefins to linear[1−4] or branched allylic acetates,[5−7] and the use of this chemistry in the synthesis of complex molecules.[8−10] Arguably, linear allylic acetates are less synthetically useful than branched allylic acetates because the former lack a stereogenic center. The use of disubstituted olefins in these reactions would produce stereogenic centers.

There are numerous reports of allylic oxidations of disubstituted olefins, such as cyclohexene.[11−14] However, acyclic disubstituted olefins are less commonly reported.[14] For example, *cis*/*trans*-2-hexene was unreactive under our reported conditions that convert terminal olefins to linear allylic acetates ($Pd(OAc)_2$, thioether (**1**, $PhS(CH_2)_2OC_6H_4$-*p*-CH_3), and benzoquinone (BQ) in acetic acid).[1] We hypothesized that the sterics about the substituted alkene may inhibit binding to the metal catalyst, which is likely required for the allylic oxidation to occur.[2] According to this hypothesis, increasing the sp^2-sp^3 carbon−carbon bond length ($C-CH_3$, ∼1.5 Å) of the olefin should decrease the steric hindrance about the metal and increase binding to the metal catalyst to allow a reaction to occur. To investigate this hypothesis, vinylsilanes were employed because the C−Si bond length is 0.3 Å longer than the C−C bond. We were also aware of the α-silyl allyl acetate product that is formed from the allylic oxidation may undergo a [3,3] rearrangement[15,16] with an additional catalyst in the same pot or in a second step to produce the branched allylic acetate product. Such a transformation would be useful since vinylsilanes are versatile intermediates in synthetic chemistry.[17] Moreover, vinylsilanes are easily prepared by hydrosilylation of the corresponding alkyne. Currently, there are no documented reports that describe metal-catalyzed allylic oxidation reactions of vinylsilanes.

Initial experiments began with the exposure of *trans*-triethyl(heptenyl)silane (**2**) to the reaction conditions shown in eq 1. The desired allylic oxidation product was not observed by GC or ^{1}H NMR spectroscopy when the reaction was conducted at 23 or 70 °C. Only starting material (**2**) was observed in the ^{1}H NMR spectrum. This unreactivity was not too surprising given that *trans*-2-hexene was also unreactive under our previous conditions. To decrease steric hindrance about the alkene even further, *cis*-triethyl(heptenyl)silane (**4**) was prepared.



Submission of *cis*-vinylsilane **4** to 10 mol % $Pd(OAc)_2$, 10 mol % **1**, and BQ in AcOH at 23 °C did not produce any oxidized product (eq 2). Increasing the temperature of the reaction to 70 °C gave 40% yield of an allylic oxidation product. Prior to spectroscopic analysis, the allylic oxidation product was expected to be the allylic acetate **3** or **5**. Analysis of the purified reaction mixture showed the product to be the branched allylic acetate containing a *trans*-vinylsilane (**5**). The product was assigned based on 1- and 2-D ^{1}H NMR spectroscopic analysis (Supporting Information) by comparison of the alkene coupling constants with previously reported *trans*-vinylsilanes.[18,19] Interestingly, this product was the only observed regioisomer by GC and ^{1}H NMR spectroscopic analysis of the crude reaction. The only other vinylic resonances in the ^{1}H NMR spectrum of this reaction were assigned to a small amount of *cis*-vinylsilane **4**. After some optimization, the use of 2 mol % $Pd(OAc)_2$ at 90 °C without external ligand (**1**) in the presence of BQ provided the optimal catalytic conditions.

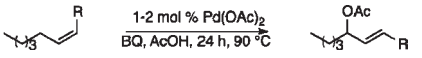


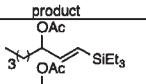
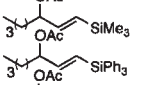
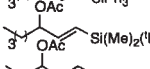
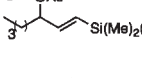
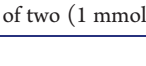
Additional reaction screening showed that the optimal silicon group was triethylsilyl (Table 1, entry 1). Replacing the triethylsilyl group with the smaller trimethylsilyl group lowered the reaction yield from 66% to 41% (entry 2). Increasing the steric bulk to the

Received: May 10, 2011
Published: October 19, 2011

dx.doi.org/10.1021/ja2089102 | *J. Am. Chem. Soc.* 2011, 133, 18503–18505

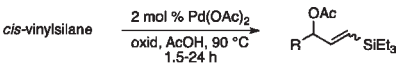
Table 1. Effect of Silyl Group Substitution on Allylic Oxidations[a]

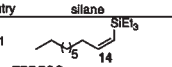
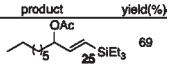
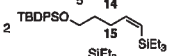
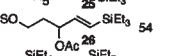
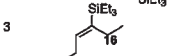
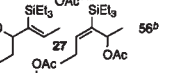
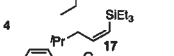
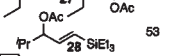
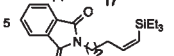
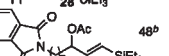
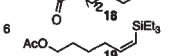
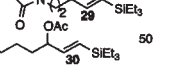
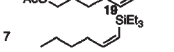
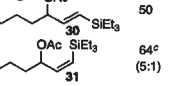
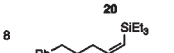
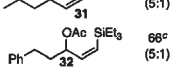
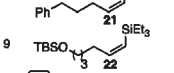
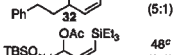
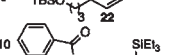
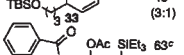
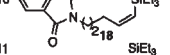
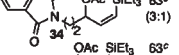
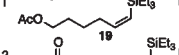
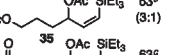
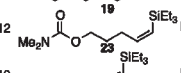
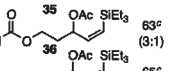


entry	silane	product		yield (%)
1	R = $SiEt_3$; **4**		**5**	66
2	R = $SiMe_3$; **6**		**10**	41
3	R = $SiPh_3$; **7**		**11**	16
4	R = $Si(Me)_2(t$Bu); **8**		**12**	44
5	R = $Si(Me)_2$(Bn); **9**		**13**	57

[a] Isolated yields are an average of two (1 mmol) reactions.

Table 2. Intermolecular Allylic Oxidations of *cis*-Vinylsilanes[a]



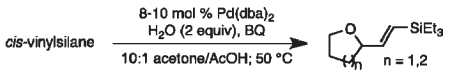
entry	silane	oxid.	product	yield(%)
1		BQ		69
2		BQ		54
3		BQ		56[b]
4		BQ		53
5		BQ		48[b]
6		BQ		50
7		PIDA		64[c] (5:1)
8		PIDA		66[c] (5:1)
9		PIDA		48[c] (3:1)
10		PIDA		63[c] (3:1)
11		PIDA		63[c] (3:1)
12		PIDA		63[c] (3:1)
13		PIDA		65[c] (5:1)

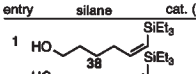
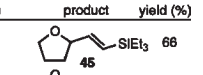
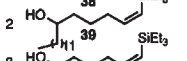
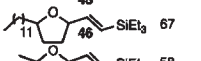
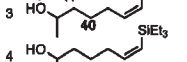
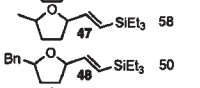
[a] Isolated yields are average of at least two (1 mmol) reactions. [b] Reactions were conducted with 5 mol % of $Pd(OAc)_2$. [c] Isolated as a mixture of *cis* (major) and *trans* (minor) mixture of diastereomers.

triphenylsilyl group lessened the yield of the reaction even further to 16% (entry 3). Other silicon groups such as *tert*-butyl dimethylsilyl and benzyl dimethylsilyl provided the desired product in 44 and 57% yield, respectively (entries 4−5).

The substrate scope of the reaction was examined under the optimized conditions (Table 2). Most all of the products within the table are regio- and diastereomerically pure when BQ was used as oxidant (entries 1−2, 4−6). Moreover, the majority of the reactions proceeded using only 2 mol % of $Pd(OAc)_2$. An increase in catalyst loading did not greatly improve the yield since this also likely increased unproductive consumption of the vinylsilane.

Table 3. Intramolecular Allylic Etherifications of *cis*-Vinylsilanes[a]



entry	silane	cat. (mol %)	t (h)	product	yield (%)
1		8	24		66
2		10	24		67
3		10	24		58
4		10	24		50
5		8	24		62
6		10	24		56
7		10	72		55

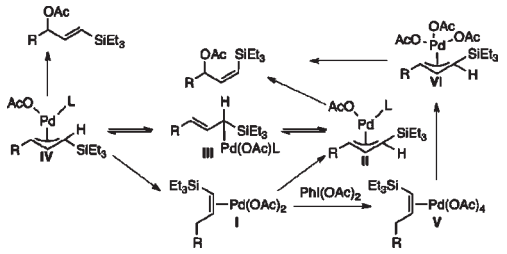
[a] Isolated yields are average of at least two (1 mmol) reactions.

However, the use of $PhI(OAc)_2$ as oxidant increased the yields of the oxidation products (entries 7−13). For example, using BQ as oxidant with phthalimide substrate (**18**) gave 48% yield of oxidation product **29** (entry 5), while the same substrate with $PhI(OAc)_2$ gave 63% yield of the desired allylic oxidation product (entry 10). The increased yields are likely an effect of the faster reaction times (≤1.5 h) with this oxidant. All products isolated using $PhI(OAc)_2$ retained the *cis*-vinylsilane as the major product.

The metal-catalyzed intramolecular cyclization of alcohols containing terminal olefins has been known for quite some time. One drawback to these methods is that the formed products typically contain a methyl group at the 2-position, limiting the diversity of the products in these reactions (eq 3).[20] Moreover, the typical need to employ substrates containing geminal disubstitution to invoke the Thorpe−Ingold effect also limits reaction scope. We discovered that exposure of vinylsilane **38** to a catalytic amount of $Pd(dba)_2$ in a 10:1 (v/v) solution of acetone and acetic acid provided 66% yield of the desired α-vinyl tetrahydrofuran product **45** (Table 3, entry 1). The acetylated product was also recovered along with a minor amount of the intermolecular acetate product. This reaction seemed general as α-substituted alcohols reacted smoothly to produce the desired vinyl tetrahydrofuran products in 50−67% yield (entries 2−6). Moreover, allylic etherification to form the tetrahydropyran **51** occurred in 55% yield (entry 7). The method is complementary to Wacker-type oxidative cyclizations, which typically employ phenol nucleophiles.[21]

The proposed reaction mechanism for the allylic oxidation of terminal olefins is thought to proceed via π-allylpalladium intermediates. In the presence of BQ as oxidant, coordination of the vinylsilane (**I**) followed by C−H activation can produce the *anti*-π−allylpalladium intermediate **II** (Scheme 1). Complex **II** can either undergo reductive elimination to produce the *cis*-vinylsilane product or can undergo $\pi-\sigma-\pi$ isomerization[22] to produce the *syn*-π−allylpalladium complex (**IV**) via (**III**). In the presence of $PhI(OAc)_2$, complex **I** likely reacts with $PhI(OAc)_2$ to produce the Pd(IV) species (**V**).[14a] Insertion of palladium into

Scheme 1. Oxidant-Controlled Diastereoselectivity



the allylic C−H bond gives complex **VI**, which can undergo C−O bond forming reductive elimination to give the *cis*-vinylsilane product. We cannot discount the potential role of Pd(III) intermediate complexes in reactions with $PhI(OAc)_2$ as oxidant, as such intermediates would also increase the rate of C−O bond forming reductive elimination.[23]

From this proposed mechanism, some assumptions can be made. First, the selective formation of the *trans*-allylic acetate product when using BQ can be explained by slow C−O bond forming reductive elimination from complex (**II**), which allows the system time to funnel to the typically more thermodynamically stable *syn*-π−allylpalladium complex (**IV**), which forms the *trans*-vinylsilane after reductive elimination. The faster reductive elimination from the Pd(IV) complex (**VI**) is likely the reason the *cis*-product is the major product using this oxidant.[14a,24] However, the rate of reductive elimination is not fast enough to completely outcompete *anti* to *syn* isomerization, hence, the appearance of *trans* product. Once the *cis*- and *trans*-allylic acetates are formed, these do not interconvert under the conditions with BQ or $PhI(OAc)_2$ as oxidant since submission of a 5:1 mixture of *cis*/*trans* vinylsilanes under either reaction condition did not alter the ratio of the diastereomers. These results suggest that the catalyst does not insert into the products to re-form complexes **II**, **IV**, or **VI**.

Upon replacing AcOH from the optimized reaction conditions with a 4:1 (v/v) solution of $AcOH/H_2O$ in the presence of $Pd(OAc)_2$ and $PhI(OAc)_2$ as the oxidant, *cis*-vinylsilane **4** was converted to the *cis*-vinylsilane allylic acetate in 45% yield. The corresponding *trans* product was not observed by ^1H NMR spectroscopy of the crude reaction mixture. As a control experiment, the corresponding *trans*-allylic acetate product (**5**) was subjected to the above reaction conditions containing water and did not decompose. This result suggests that both products are not being formed concurrently. The starting material is completely consumed in the reaction. The amount of water appears to increase catalyst or reaction intermediate decomposition rate, thus, decreasing the reaction yield. The selectivity observed by the addition of water may be caused by an increase in the rate of C−O reductive elimination or by somehow shutting down the *syn*- to *anti*-π−allylpalladium isomerization pathway.[25]

In summary, the allylic oxidation of *cis*-vinylsilanes to produce branched allylic acetate *cis*- or *trans*-vinylsilane compounds occurs in the presence of catalytic $Pd(OAc)_2$. This reaction with BQ as oxidant solely provides the branched, *trans*-silyl allylic acetate product, while the use of $PhI(OAc)_2$ as oxidant provides the *cis*-silyl allylic acetate as the major product. The first intramolecular allylic C−H etherification of *cis*-vinylsilanes produced five- and six-membered oxygen heterocycle products that retained the vinylsilane functionality. The reaction pathway is being examined in order to suppress the deleterious side reaction and better understand the observed selectivities.

■ ASSOCIATED CONTENT

Supporting Information. Experimental procedures and spectral characterization of all new compounds. This material is available free of charge via the Internet at http://pubs.acs.org.

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■ ACKNOWLEDGMENT

The authors thank The Ohio State University for the generous support of this research and the Ohio BioProduct Innovation Consortium for supporting the mass spectrometry facility.

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