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Intramolecular Endo-Dig Hydrosilylation Catalyzed by Ruthenium: Evidence for a New Mechanistic Pathway

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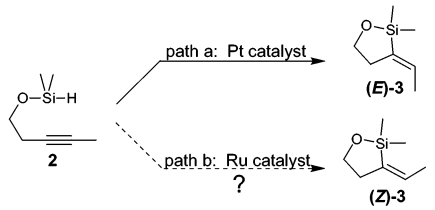
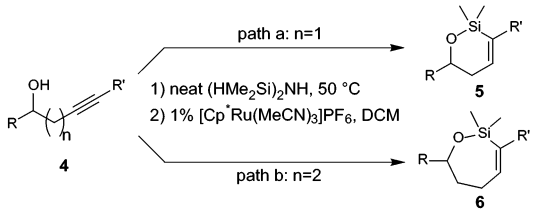
Trisubstituted vinylsilanes are important synthetic intermediates due to their tunable reactivity, chemical stability, low cost, and low toxicity. However, the most straightforward access to such compounds—hydrosilylation of internal alkynes—has not been well-studied due to issues of regioselectivity and reactivity.[1] Having previously reported a stereoselective trans hydrosilylation of internal alkynes by a cationic ruthenium complex, $[Cp^*Ru(MeCN)_3]PF_6$ (**1**),[2] we hoped to extend the utility of the complex to selective intramolecular hydrosilylation.



(1)

Intramolecular hydrosilylation has been reported by several groups, and the platinum-catalyzed reaction (eq 1, path a) efficiently generates exocyclic vinylsilane products of defined (*E*) configuration useful for a variety of subsequent transformations.[3−5] Ruthenium-catalyzed reactions are more complex because of the propensity for ruthenium to effect a trans hydrosilylation. Since it is generally proposed that trans hydrosilylation derives from an initial cis silylmetalation followed by isomerization, the expectation was that the same regioselectivity as that for the platinum-catalyzed process would be observed, but that the opposite geometrical isomer would ultimately be formed (eq 1, path b).[6]

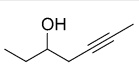
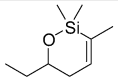
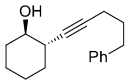
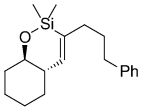
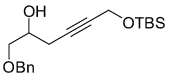
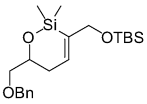
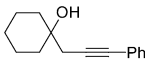
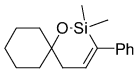
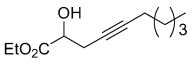
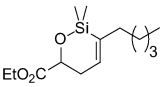
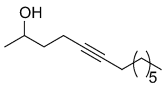
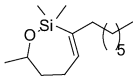
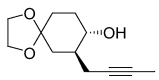
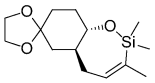
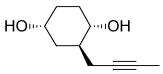
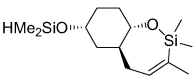
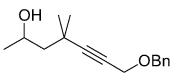
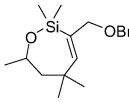


(2)

In the event, homopropargylic alcohols **4** ($n = 1$) were silylated in neat tetramethyldisilazane (TMDS) and subjected to reduced pressure to remove residual TMDS.[4] The residue was then taken up in dichloromethane and treated with the ruthenium complex **1** (eq 2, path a). A clean ensuing reaction produced not the expected exo-dig cyclization product (as shown in eq 1b), but rather the endo-dig product **5**, the result of a net trans addition. The only reported hydrosilylation producing similar endo products is that catalyzed by strong Lewis acids with 4-alkynyl-silanes.[7]

Although propargylic alcohols are unreactive, a wide variety of homopropargylic and bis-homopropargylic alcohols proceed well in the ruthenium-catalyzed process (Table 1). Interestingly, the latter also gave endo-dig cyclization—in this case to provide seven-membered ring products even though the exo-dig process would form the more favorable six-membered ring. A variety of substitution patterns and functionality are tolerated, including substantial steric bulk at the alcohol (entry d), and alkyne (entry i). A diol (entry h) was readily bis-silylated and underwent clean hydrosilylation at the only accessible silane—leaving the other untouched—indicating that insertion into the silicon−hydrogen bond is reversible. In all cases, only a single product isomer is observed—indeed, the reaction is sufficiently clean that in several cases (entries a, d, f, and i) the crude reaction mixture could be filtered through Florisil to afford vinylsilane product of >95% purity without additional purification. In other cases, purification was performed on Florisil.

Table 1. Intramolecular Alkyne Hydrosilylation of Homo- and Bis-homopropargylic Alcohols[a]

Entry	Alkyne	Ru cat. **1**	Product	Yield[b]
a		1%		79[c]
b		1%		85
c		1%		86
d[d]		5%		95
e		3%		77
f		1%		97
g		3%		78
h		3%		85
i[e]		10%		92

[a] Conditions: (a) 3 equiv $(Me_2HSi)_2NH$, neat, 50 °C. (b) cat. $[Cp^*Ru(MeCN)_3]PF_6$ in CH_2Cl_2, 0 °C to rt. [b] Isolated yield after purification on Florisil. [c] Modest yield due at least in part to volatility of product vinylsilane. [d] Silylation performed at 60 °C. [e] Silylation performed at 80 °C.

Synthetically, the hydrosilylation presented affords access to vinylsilanes not otherwise readily available. Such vinylsilane products can serve as precursors for the regioselective synthesis of

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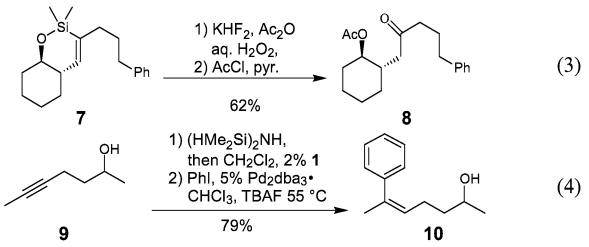
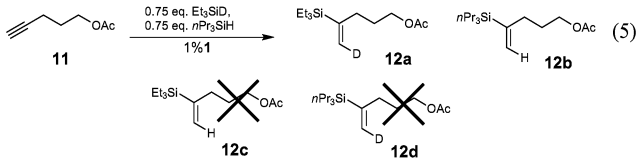
ketones by oxidation, as shown for silane **7** (eq 3).[8] Thus, such γ-hydroxy ketones now readily derive from the simple addition of an alkyne and an epoxide. Alternatively, the vinylsilane products can be used in subsequent cross-coupling reactions to afford trisubstituted olefins of defined stereochemistry (eq 4).[3,6]



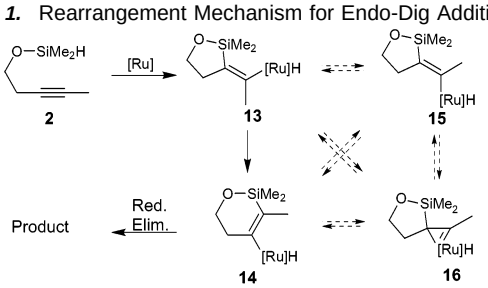
From a mechanistic point of view, these results force a new examination of the pathways providing trans hydrometalation reactions. The generally accepted mechanism of trans hydrosilylation reactions was postulated from analysis of terminal alkyne hydrosilylation reactions catalyzed by rhodium and iridium complexes.[9] Under this theory, an initial *syn*-silylmetalation precedes cis/trans isomerization, and finally reductive elimination. The limited number of reports of trans addition with ruthenium complexes with terminal alkynes have generally assumed that such a mechanism is operable for this metal as well.

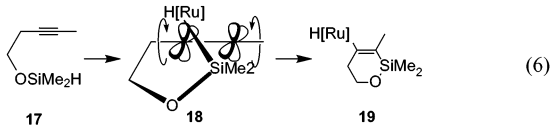


However, the endo-dig results presented here suggest a different mechanism, as *syn*-silylmetalation would produce a silylcyclohexene (for the homopropargylic case) with trans olefin geometry—an unlikely case. Among the possibilities, routes involving external attack on a coordinated alkyne as in Lewis acid-catalyzed reactions[7] or those involving two discreet ruthenium complexes are unlikely due to a crossover experiment (eq 5)—in which crossover products (**12c** or **12d**) or doubly deuterated products are not observed—indicating that a concerted process is at work.[10]

Of the first-order processes, initial exo-dig silylmetalation—followed by a series of rearrangements—cannot be ruled out but has no precedent nor appears to be likely, given the nature of the intermediates (Scheme 1).[11] Alternatively, the most straightforward explanation for the observed products is perhaps a direct trans addition of the silicon−ruthenium bond across orthogonal π-systems of the alkyne (eq 6).[12] An intramolecular endo-dig hydro*acylation* has been reported with rhodium. In that case, an initial *cis*-hydrometalation does occur which could be followed by some internal rearrangement analogous to that in Scheme 1.[13] However, in that case reductive elimination from an initial cis hydrometalation is disfavored due to the subsequent formation of a cyclobutanone.

Scheme 1. Rearrangement Mechanism for Endo-Dig Addition





The complex **1** effects intramolecular hydrosilylation producing products of unique regiochemistry under very mild conditions with excellent selectivity. In addition to producing valuable intermediates thus far obtainable only in a circuitous fashion, the results require a reexamination of the mechanism surrounding trans-hydrosilylation reactions with ruthenium catalysts. At the very least, a simple cis addition/isomerization mechanism almost certainly cannot be active in this case. A silicon−ruthenium transposition could potentially provide a rationalization. However, the evidence for any products of syn addition with nonhydrido ruthenium catalysts is very scarce.[14] Alternatively, a direct trans addition to orthogonal π-systems is also a possibility. Preliminary data in these laboratories that hydrosilylation of allenes—but not olefins—with **1** does proceed supports the notion that orthogonal π-orbitals are necessary for reactivity. Further investigations probing the mechanism and synthetic utility of this process are ongoing.

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Supporting Information Available: Experimental details and characterization data as well as GC−MS traces from Figure 1 (PDF). This material is available free of charge via the Internet at http://pubs.acs.org

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(10) Addition products analyzed by GC−MS. The trans stereochemistry of addition for terminal alkynes has been established in a related experiment. See Supporting Information.
(11) Although the conversion of **13** to **14** can be envisioned, the absence of any products derived from reductive elimination of the intermediates, together with the lack of an obvious thermodynamic driving force for these interconversions make such a route difficult to accept.
(12) It is also possible that direct trans addition is facilitated by a dinuclear ruthenium complex, provided that only one silane molecule is involved. For a recent report with evidence of a trans hydrometalation with a dinuclear ruthenium complex, see: Martin, M.; Sola, E.; Lahoz, F. J.; Oro, L. A. *Organometallics* **2002**, *21*, 4027−4029. However, our evidence precludes the involvement of species such as those presented therin.
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