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Copper-Catalyzed Highly Regioselective Silylcupration of Terminal Alkynes to Form α-Vinylsilanes

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Supporting Information

ABSTRACT: A highly regioselective synthesis of branched vinylsilanes through silicon−copper additions to terminal alkynes catalyzed by copper(I) was developed using methanol as additive. The corresponding vinylsilanes were obtained with excellent branched to linear selectivity of up to 99/1 in good yields.

Organosilanes are versatile building blocks in organic synthesis and material chemistry.[1] Among them, vinylsilanes have been known to be attractive intermediates since they can serve as stable vinylic anion or cation synthetic equivalents.[2] However, the widespread utilization of these compounds has been impeded by the lack of practical methods for accessing stereo- and regiodefined vinylsilanes. The most straightforward and atom-economical method to access vinylsilanes is via the regioselective hydrosilylation of alkynes.[3] However, only few catalytic systems, such as Ru-based catalysts, have been established for the generally selective synthesis of α-vinylsilanes.[4] Apart from this, the silylmetalation of alkynes offers an alternative and attractive strategy for the efficient synthesis of stereodefined vinylsilanes.[5] For instance, Uchiyama et al. employed a bulky zincate (SiBNOL-Zn-ate) to promote the chemo- and regioselective silylzincation of terminal alkynes, affording α-vinylsilanes without any catalyst.[6] However, it is still a challenge to gain highly branched selectivity with general terminal alkynes through silylcupration.[7] Recently, many research groups reported Cu−B additions to multiple bonds through activation of $B_2(pin)_2$ with copper alkoxide,[8] and the similar strategy was applied to form a C−Si bond.[9,10] Herein we report the low-cost copper-catalyzed highly chemo- and regioselective silylcupration of unfunctionalized and functionalized terminal alkynes based on Si−B activation,[11] resulting in a high degree of Markovnikov selectivity (Scheme 1).

Table 1 summarizes the representative results for the silylcupration reaction of 1-octyne. The reaction of 1-octyne with $PhMe_2SiB(pin)$ was carried out in the presence of CuCl (10 mol %) and NaO*t*Bu (11 mol %) in THF under different reaction conditions. Various phosphine ligands were screened to improve the selectivity and yield. In the presence of the bidentate ligand dppe, the product was obtained in 47% isolated yield without regioselectivity (**B**:**L** 50:50; Table 1, entry 1). Later dppf and Xantphos ligands were tried; vinylsilanes were obtained in poor yields, but with good linear to branched selectivities (entries 2 and 3). Interestingly, the regioselectivity was reversed when using PEt_3 and the desired α-vinylsilane was obtained in moderate yield (entry 4). On the basis of these results, we proposed that the utilization of electron-rich and bulky monophosphine ligands might increase reactivity and improve selectivity. Better yield and regioselectivity were indeed observed when using $PtBu_3$ (entry 5). It was gratifying to find that the reaction gave the best results with good yield of 80% and excellent regioselectivity (**B**:**L** 99:1) at 0 °C with the stable Johnphos ligand developed by Buchwald (entry 7).[12] When the reaction was performed at ambient temperature, better yield was achieved, albeit with slight deterioration of selectivity (entry 8).

Scheme 1. Isomers in the Silylcupration of Terminal Alkynes Based on Si−B Activation Catalyzed by Copper

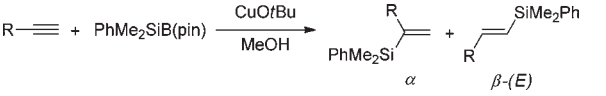
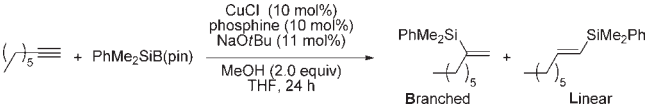


Table 1. Copper-Catalyzed Silylcupration of 1- Octyne[a]



entry	phosphine	*T* (°C)	yield (%)[b]	ratio (B:L)[c]
1	dppe	−20	47	50:50
2	dppf	−20	14	18:82
3	Xantphos	−20	12	5:95
4	PEt_3	−20	62	86:14
5	$PtBu_3$	−20	70	93:7
6	Johnphos	−20	73	99:1
7	***Johnphos***	***0***	***80***	***99:1***
8	Johnphos	rt	93	95:5

[a] Reaction conditions unless otherwise specified: 1-octyne (0.3 mmol, 1 equiv), $PhMe_2SiB(pin)$ (1.1 equiv), CuCl (0.1 equiv), phosphine (0.1 equiv), NaO*t*Bu (0.11 equiv) and MeOH (2.0 equiv) in THF (1.0 mL) for 24 h. [b] Isolated yields of the mixture of isomers. [c] Determined by ^1H NMR analysis of the crude mixture.

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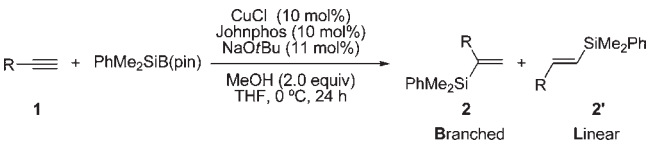
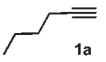
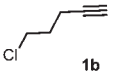
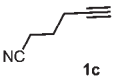
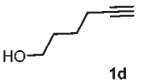
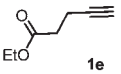
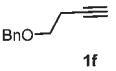
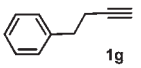
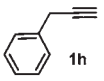
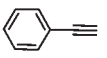
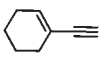
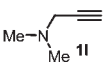
Table 2. Highly Branch-Selective Synthesis of Vinylsilanes of Various Terminal Alkynes Catalyzed by Copper[a]

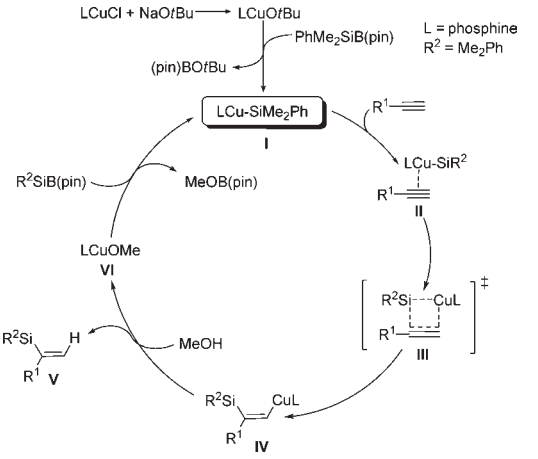


entry	reactants	yield (%)[b] 2+2'	ratio[c] B:L
1	 1a	71	97:3
2	 1b	74	96:4
3	 1c	67	95:5
4	 1d	86	99:1
5	 1e	90	93:7
6	 1f	60	96:4
7	 1g	70	96:4
8	 1h	76	99:1
9	 1i	87	62:38
10	 1j	76	93:7
11	 1k	84	90:10
12	 1l	50	91:9

[a] Conditions: **1** (0.3 mmol), $Ph(Me)_2SiB(pin)$ (0.33 mmol), CuCl (0.03 mmol), NaO*t*Bu (0.033 mmol), Johnphos (0.03 mmol) and MeOH (2.0 equiv) in THF (1.0 mL), nitrogen, 0 °C, 24 h. [b] Isolated yields of the mixture of isomers. [c] Determined by ^{1}H NMR analysis of the crude mixture.

With the optimized conditions in hand, we next tested the scope of the reactions using various terminal alkynes. The results are summarized in Table 2. Substrates possessing both electron-donating (entries 4, 6, and 12) and electron-withdrawing groups (entries 2, 3, and 5) all can react efficiently. A wide range of functional groups, including halide, cyano, ester, hydroxyl, and protected amino groups, are tolerant, and the substrate bearing an ester group gave the best yield (entry 5). Terminal alkynes containing alkyl, benzyl, cycloalkyl groups also showed highly

Scheme 2. Proposed Catalytic Cycle for Silicon−Copper Additions to Terminal Alkynes



branched regioselectivities (entries 1, 8, and 11). It was noteworthy that double bond moiety in the substrate remained intact (entry 10). Another important feature of the process was that coordinating groups did not affect the regioselectivities (entries 6 and 12), though only moderate yields were obtained. When phenylacetylene was employed as a substrate the regioselectivity dramatically decreased presumably due to the electron deficient nature of the terminal alkyne carbon (entry 9).

Until now the mechanism of the silylcupration of acetylenes has not been well-studied in literature. To the best of our knowledge, there is only one proposed mechanism that is similar to the carbocupration reaction.[7d] It was previously proposed that the carbocupration of alkynes proceeds via direct 1,2-addition of R-Cu to the alkyne, leading to the four-centered addition intermediate, and the Cu(I) oxidation state remains unchanged during the reaction.[13] Later Nakamura et al. deduced through systematical calculations that the carbocupration reaction proceeds via an oxidative addition to give a Cu(III) species which undergoes reductive elimination to give the vinyl copper species.[14] On the basis of our experimental results, a plausible catalytic cycle is shown in Scheme 2. We believe that a LCu(I)Cl complex could easily react with NaO*t*Bu to form a LCuO*t*Bu complex, which undergoes formal σ-bond metathesis with $PhMe_2SiB(pin)$ to generate the Cu−Si key intermediate **I**. In order to prove initial Si−B activation by a LCuO*t*Bu complex, *t*BuOH instead of MeOH was used as additive with model reaction conditions (Table 1, entry 7), and similar results were gained (**B:L** 96:4, 79% yield). This supports our proposed initial activation step, although a LCuOMe complex is catalytically active when using NaO*t*Bu (11 mol %) in excess MeOH (2.0 equiv). Then, Cu of the Cu−Si key intermediate **I** coordinates with the alkyne substrate to give complex **II**. Subsequently the C−C triple bond inserts into the Cu−Si bond, forming vinyl copper species **IV**, through a possible four-membered transition state **III**. Finally the vinyl copper species undergo protonolysis in the presence of methanol to afford the product **V** and regenerate the catalyst **VI** LCuOMe complex. It should be noted that another mechanistic pathway which involves an oxidative addition and reductive elimination process is also possible and cannot be ruled out.[7d]

In conclusion, we have demonstrated an efficient way for the highly Markovnikov-selective silylcupration of various terminal

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alkynes. The reaction is tolerant to a wide range of functional groups, including chloride, hydroxyl, ester, cyano, amino groups and gives α-vinylsilanes in moderate to good yields with excellent regioselectivities. This method, using the low-cost transition metal copper, provides a new entry for the construction of the C−Si bond and opens up many possibilities of installing Si into organic molecules via Cu−Si intermediates. Efforts to delineate the mechanism and to apply this method to other addition reactions are in progress.

■ ASSOCIATED CONTENT

Supporting Information. Additional experimental procedure and spectral data. This material is available free of charge via the Internet at http://pubs.acs.org.

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