Organic LETTERS
Letter
pubs.acs.org/OrgLett

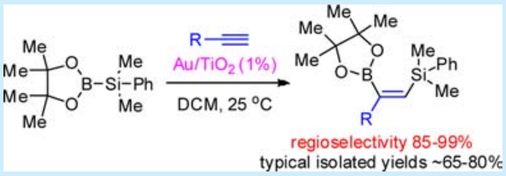
Nanogold-Catalyzed *cis*-Silaboration of Alkynes with Abnormal Regioselectivity

Charis Gryparis and Manolis Stratakis*

Department of Chemistry, University of Crete, Voutes 71003 Iraklion, Greece

Supporting Information

ABSTRACT: The first example of gold-catalyzed silaboration of alkynes with $PhMe_2SiBpin$ is documented in the presence of supported gold nanoparticles. In the case of terminal alkynes, the reaction proceeds at ambient conditions in very good yields and the regioselectivity is opposite to that observed in the presence of Pd or Pt catalysts. The abnormal regioselectivity is attributed to steric factors imposed by the Au nanoparticle during the 1,2-addition of silylborane to the alkyne.

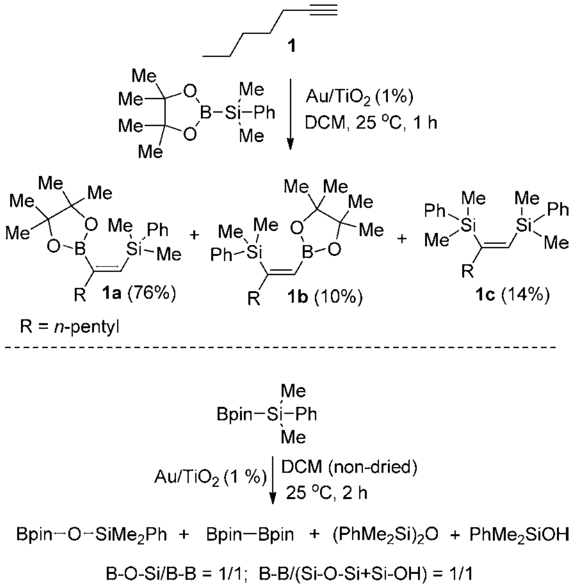


regioselectivity 85-99%
typical isolated yields ~65-80%

The reaction among σ silylboranes and alkynes under catalysis by Pd(0) and Pt(0) provides *cis*-1,2-addition products,[1] useful precursors for the synthesis of stereodefined functionalized alkenes[2] via Hiyama and Suzuki cross-coupling reactions at the C−Si or C−B functionalities, respectively. The accepted reaction mechanism involves oxidative insertion of the Si−B bond on metal (M^0) forming a (silyl)M^{II}(boryl) intermediate that undergoes insertion from the alkyne. Finally, reductive elimination of the metal affords the *cis*-1,2-addition products. Products with opposite configuration (*trans*-addition) can be obtained by tuning the stoichiometry of the reactants in favor of the silylborane.[3] Typically, in the case of terminal alkynes, the boryl functionality is attached on the terminal carbon atom of the alkyne, while the silyl group is on the internal one (1-boryl-2-silyl-1-alkenes).[4] A remarkable switch in regioselectivity of silaboration to yield 2-boryl-1-silyl-1-alkenes was observed by using a very bulky phosphine as ligand [*o*-biphenyl(*t*-Bu)$_2$P] and $(n^3\text{-}C_3H_5)$Pd(L)Cl as catalyst.[5]

As it has been recently shown that 1,2-disilanes[6] or distannanes[7] undergo oxidative insertion on Au(I), forming bis(silyl) or stannylgold(III) complexes, it would be compelling to uncover the ability of gold to catalyze the addition of silylboranes to alkynes, just as Pd(0) or Pt(0) do. For instance, the stereoselective *syn* insertion of the gold−silicon bond from $Ph_3PAu\text{-}SiR_3$ to alkynes has been recently documented.[8] The interest in the so far unknown gold-catalyzed silaboration originates from the recent results from our group regarding the activation of σ disilanes by gold nanoparticles (Au NPs). While typical homogeneous Au(I) catalysts seem to be unreactive, Au NPs supported on metal oxides[9] are efficient catalysts. Thus, Au/TiO_2 catalyzes the hydrolysis/alcoholysis[10] of Si−Si linkage and the *cis*-selective addition of 1,2-disilanes to alkynes.[11] The mechanism possibly involves oxidative insertion of the Si−Si moiety on gold nanoparticles.[12] This precedent urged us to examine the possible reaction among silylboranes and alkynes in the presence of Au/TiO_2. The readily available and fairly stable $PhMe_2SiBpin$ [pin = pinacolato] was chosen. Upon mixing 1.0 equiv of heptyne (**1**) with 1.2 equiv of $PhMe_2SiBpin$ in DCM under strictly dry conditions, we observed after addition of Au/TiO_2 (1 mol %) the smooth consumption of alkyne within 1 h at 25 °C, with primarily formation of the 1,2-silylboration product **1a** in 76% relative yield and its regiosomer **1b** in 10% relative yield (Scheme 1). In addition, 14% of the 1,2-disilylation product **1c**[11] was seen, as well as equimolar amounts of pinB-Bpin [bis(pinacolato)diboron] relative to **1c**. It is remarkable that the observed regioselectivity is opposite to what has been seen under typical Pd or Pt catalyst conditions, except a specific case commented earlier[5] utilizing an extremely bulky phosphine as ligand. Increasing the amount of $PhMe_2SiBpin$ to 3 equiv results to a faster consumption of **1**.

Scheme 1. Reaction of $PhMe_2SiBpin$ with 1-Heptyne (1) and Its Hydrolysis in the Presence of Au/TiO_2



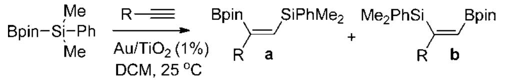
Received: January 22, 2014
Published: February 17, 2014

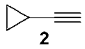
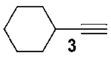
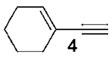
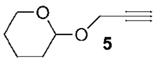
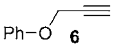
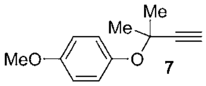
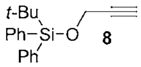
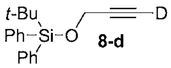
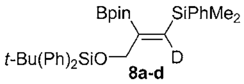
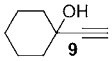
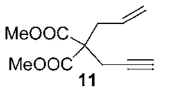
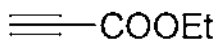
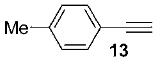
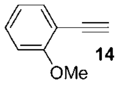
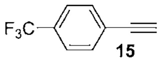
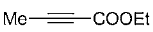
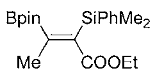
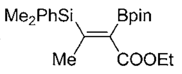
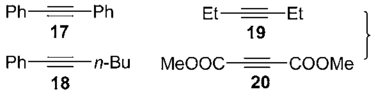
dx.doi.org/10.1021/ol500225x | *Org. Lett.* 2014, 16, 1430−1433

Yet, the relative yield of side product **1c** increases to 30%. The amount of **1c** can be reduced to <10% by slow addition of $PhMe_2SiBpin$ into the reaction mixture over the reaction time period (~1 h). Under this modification, silaboration product **1a** can be obtained in 72% isolated yield after column chromatography. Au/Al_2O_3 provides even better regioselectivity (**1a**/**1b** = 94/6), yet the reaction rate is slow and the amount of disilyl side product **1c** increases substantially to 25%. In the presence of Au/ZnO, the reaction rate is even slower, the ratio **1a**/**1b** = 85/15, and the isolated yield of **1a** below 50%. Notably, the Au/TiO_2-catalyzed reaction can be performed in nondried DCM under open air conditions, at the expense of $PhMe_2SiBpin$ (typically 1.5 equiv) to compensate its partial hydrolysis, yielding $PhMe_2Si$-O-Bpin. The formation of side disilylation adduct **1c** along with pinB-Bpin arises from a competing pathway, as by mixing $PhMe_2SiBpin$ with nondried DCM and subsequent treatment with Au/TiO_2 (1%) resulted after 2 h in the disappearance of silylborane and formation of the fairly unstable hydrolysis product $PhMe_2Si$-O-Bpin,[13] pinB-Bpin, and an equimolar diborane mixture of $PhMe_2SiOH$ + $(PhMe_2Si)_2O$ which varies with time (Scheme 1). Traces of $PhMe_2SiH$ were also detected. The relative ratio $PhMe_2Si$-O-Bpin/pinB-Bpin was ~1/1. Apparently, a metal-catalyzed silylborane methathesis is taking place, forming diborane and disilane; the latter undergoes hydrolysis under the reaction conditions, forming silanol and 1,3-disiloxane via the transient participation of $PhMe_2SiH$[10] (see also the mechanistic analysis in Scheme 2). Pd-catalyzed analogous element−element σ bond metatheses in disilanes[14] and silylstannanes[15] are already known. The reaction is heterogeneous as leaching of gold into the supernatant solution under of the reaction conditions is below parts per billion level (ICP analysis) as also observed in the disilylation[11] reaction. Among homogeneous Au(I) catalysts tested in the reaction of **1** with $PhMe_2SiBpin$, only $Ph_3PAuNTf_2$ (3 mol %) provided traces of products after heating at 70 °C in DCE for 12 h (~1% yield; **1a**/**1b** = 50/50). In the meantime, ~4% of $PhMe_2SiBpin$ had been disproportionated to pinB-Bpin and ~20% into $PhMe_2SiOBpin$ via hydrolysis by residual water.

The scope and limitations of the Au/TiO_2-catalyzed silaboration were examined with various functionalized alkynes. The results are presented in Table 1.[16] In our experiments, a series of terminal alkynes reacted smoothly with excess of $PhMe_2SiBpin$ (typically 1.5 equiv) in nondried DCM (1.0 mol % of gold from Au/TiO_2). The reaction proceeds in good to excellent yields in favor of 2-boryl-1-silyl-1-alkenes (products **a**). The regioselectivity (**a**/**b**) varies from 85/15 to >99/1, while the stereochemistry of all silaboration adducts is >97% *cis* (*E* configuration) as proven by NOE experiments. In all cases under the reaction conditions, *cis*-1,2-disilylation adducts are also formed in 2−15% relative ratio, which can be removed with column chromatography. Alkynes with pronounced steric hindrance adjacent to the internal acetylenic carbon atom exhibit the highest regioselectivity of silaboration, providing essentially only one regioisomer (e.g., products **7a**, **9a**, and **11a**). Notably, CF_3-substituted aryl alkyne **15**, which is unproductive under Pd catalysis conditions,[5] forms product **15a** in good yield. Also, enyne **11** which is extremely unreactive[17] provides silaboration adduct **11a** in low yield due to an extensive disilylation as a single regioisomer. No cyclization product(s) were seen in the crude reaction mixture as occurs[5] in the presence of $(\eta^3\text{-}C_3H_5)Pd[o\text{-biphenyl}(t\text{-}Bu)_2P]Cl$. In general, increasing the molar equivalents of

Table 1. Addition of $PhMe_2SiBpin$ to Alkynes Catalyzed by Au/TiO_2



alkyne	relative ratio **a**/**b**	yield of **a**[a]/time
 **2**	87/13	70%/2 h
 **3**	94/6	74%/5 h
 **4**	93/7	81%/2 h
 **5**	83/17	68%/1 h
 **6**	90/10	72%/2 h
 **7**	99/1	59%/5 h[b]
 **8**	94/6	76%/1 h
 **8-d**	 **8a-d**	
 **9**	99/1	86%/1 h
 **10**	86/14	67%/1 h
 **11**	99/1	19%/36 h[c]
 **12**	85/15	65%/1 h
 **13**	89/11	75%/1 h
 **14**	92/8	75%/1 h
 **15**	85/15	62%/6 h
 **16**[d]	 **16a** (16%)[e]	 **16b** (17%, *E*/*Z* = 4/1)[e]
 **17** **19** **18** **20** unreactive alkynes		

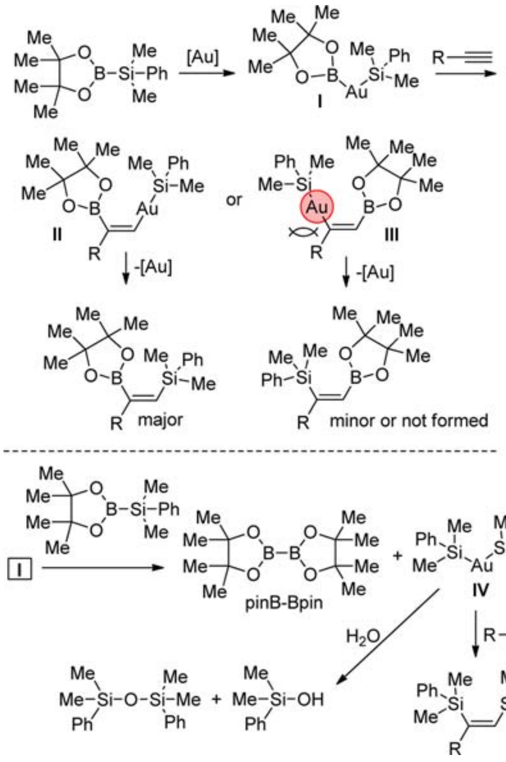
[a]Isolated yield of the major regioisomer **a**. [b]With 2.5 equiv of $PhMe_2SiBpin$. The lower yield of **7a** is due to partial cleavage of 4-methoxyphenol under chromatographic conditions. [c]With 6 equiv of $PhMe_2SiBpin$, 36 h. The low isolated yield of **11a** is due to the competing formation of disilylation product in ~70% relative yield. [d]With 4 equiv of $PhMe_2SiBpin$, 12 h. The low yield of **16a,b** is due to the formation of disilylation products in ~55% relative yield. [e]Isolated yield.

$PhMe_2SiBpin$ results in gradual increase of the 1,2-disilylation products, lowering the yield of the desired silaboration pathway (e.g., enyne **11**).

A series of internal alkynes examined herein are unproductive. The possible reasons for this unreactivity, as well as the importance of steric hindrance of alkyne in controlling the regioselectivity of silaboration, will be analyzed in the accompanying mechanistic discussion. An exception among internal alkynes is acetylenic ester **16**, which yields excess of $PhMe_2SiBpin$ (4 equiv) an almost equimolar mixture of regioisomers **16a** and **16b** (**16a**/**16b** = 48/52) in relatively low yield due to competing 1,2-disilylation. Addition product **16b** appears as a mixture of double bond isomers ($E/Z \sim 4/1$). The enhanced reactivity of this specific substrate has already been shown in its dehydrogenative cyclization with a series of 1,*n*-dihydro 1,*n*-oligosilanes[17] and ascribed to its low-energy LUMO.

The Au-catalyzed addition of $PhMe_2SiBpin$ to the deuterium-labeled alkyne **8-d** (95% D, Table 1) revealed almost complete deuterium retention in product **8a-d** (94% D), which excludes the formation of gold acetylides as intermediates. Also, as Au/TiO_2 is inefficient in catalyzing hydroboration of alkynes,[18] a pathway involving cross-coupling among a terminal alkyne and $PhMe_2SiBpin$ to form silyl alkyne + hydroborane (pinBH) followed by hydroboration of the internal silyl alkyne with pinBH is also excluded. In Scheme 2, we present a mechanistic rationalization, postulating cationic gold[9,12] as the reactive catalytic sites of Au/TiO_2, capable of undergoing oxidative insertion from the Si−B bond (intermediate **I**), as already proposed in the case of σ disilanes.[11] Intermediate **I** adds to the alkyne, forming either **II** or **III**. Intermediates of type **III** have been proposed[4] in the Pd- or Pt-catalyzed silaboration of terminal alkynes and type **II** only when an extremely bulky phosphine is ligated on Pd.[5] In our case, we suggest that **III** is destabilized by the steric interactions among the Au NP-bound silane and the germinal R group. In other words, the metal preferentially binds on the terminal carbon atom of alkyne. This concept explains the lack of reactivity of internal alkynes, as steric interactions among Au NP and the alkyne substituents are developing at any binding approach, not counting the steric hindrance among the substituents of the internal alkyne who become *cis* to each other in the transition state of the addition. In the case of ester **16**, surprisingly, there is not any electronic preference for the formation of the regioisomeric adducts (**16a** and **16b** are formed in almost equal amounts),[19] but solely steric factors operate, as the hindrance imposed to the C-bound Au moiety by a methyl group (formation of product **16b**) or an ester functionality (formation of **16a**) is more or less the same. A similar regioselectivity profile has been previously seen by us in the Au/TiO_2-catalyzed hydrosilylation of **16**.[20] An additional competing pathway also operates, which involves σ bond metathesis among intermediate **I** and a neutral $PhMe_2SiBpin$ molecule that generates $PhMe_2Si$-Au-$SiMe_2Ph$ (**IV**) and pinB-Bpin. The diborane is unreactive[21] under gold nanoparticle catalysis conditions toward triple-bond 1,2-diboration. Recently, it was reported that pinB-Bpin diborylates alkynes in the presence of a nanoporous gold material as catalyst.[22] Similar σ bond metatheses are known in 1,2-disilanes[14] and 1,2-silylstannanes.[15] Intermediate **IV** undergoes *cis*-addition to alkynes, forming the 1,2-disilylation side products,[11] or is captured by H_2O[10] to form eventually $(PhMe_2Si)_2O$. In general, increasing the molar equivalents of $PhMe_2SiBpin$ relative to the alkyne results in an increase of the relative yield of 1,2-disilyl side products due to the operation of the σ bond metathesis pathway (see, for example, the cases of alkynes **11** and **16**). The preferential delivery of the Bpin moiety, relative to the silyl group on the alkyne in the proposed intermediates **II** and **III**, has already been rationalized in terms of thermodynamics.[23] The C−B bond is more stable compared to the C−Si by approximately 24 kcal/mol, which is a larger difference upon comparing the dissociation energies among the Au−B and Au−Si bonds (87.8 and 74.8 kcal/mol, respectively). Au−Si insertion from intermediate **I** to the alkynes cannot be excluded, but is unlike on the basis of thermodynamics as analyzed above and the lack of cyclization products in the silaboration of 1,6-enyne **11**.

Scheme 2. Proposed Mechanism for the Regioselective Au-Catalyzed Reaction of Silylboranes with Terminal Alkynes



In conclusion, we have presented herein the first example of a Au-catalyzed silaboration of alkynes with $PhMe_2SiBpin$. The reaction proceeds under mild conditions, no external additives or ligands are necessary, while the regioselectivity is abnormal, providing 2-boryl-1-silyl-1-alkenes which can be formed under Pd catalysis conditions only utilizing an extremely bulky phosphine as additive.[5] Additionally, $PhMe_2SiBpin$ undergoes gold-catalyzed disproportionation to disilane and diborane via σ bond metathesis. Once more, the ability of gold to catalyze reactions so far feasible with Pd, Pt, and other late transition metals is expanding its significance in synthetic organic chemistry.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Copies of ^1H, ^{13}C NMR of all products, and selected NOE experiments for key compounds. This material is available free of charge via the Internet at http://pubs.acs.org.

AUTHOR INFORMATION

Corresponding Author

*E-mail: stratakis@chemistry.uoc.gr.

Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

This work was supported by the project "IRAKLEITOS II-University of Crete" of the Operational Programme for Education and Lifelong Learning 2007-2013 (E.P.E.D.V.M.) of the NSRF (2007-2013), which is cofunded by the European Union (European Social Fund) and National Resources. We thank ProFI (ITE, Heraklion, Greece) for obtaining the HRMS spectra of unknown compounds.

REFERENCES

(1) (a) Oestreich, M.; Hartmann, E.; Mewald, M. *Chem. Rev.* **2013**, *113*, 402. (b) Ohmura, T.; Suginome, M. *Bull. Chem. Soc. Jpn.* **2009**, *82*, 29. (c) Beletskaya, I.; Moberg, C. *Chem. Rev.* **2006**, *106*, 2320. (d) Suginome, M.; Ito, Y. *Chem. Rev.* **2000**, *100*, 3221. (e) Beletskaya, I.; Moberg, C. *Chem. Rev.* **1999**, *99*, 3435.

(2) (a) Jiao, J.; Nakajima, K.; Nishihara, Y. *Org. Lett.* **2013**, *15*, 3294. (b) Ohmura, T.; Oshima, K.; Suginome, M. *Organometallics* **2013**, *32*, 2870. (c) Saito, N.; Saito, K.; Sato, H.; Sato, Y. *Adv. Synth. Catal.* **2013**, *355*, 853. (d) Zhou, H.; Moberg, C. *J. Am. Chem. Soc.* **2012**, *134*, 15992.

(3) Ohmura, T.; Oshima, K.; Suginome, M. *Chem. Commun.* **2008**, 1416.

(4) (a) Suginome, M.; Nakamura, H.; Ito, Y. *Chem. Commun.* **1996**, 2777. (b) Suginome, M.; Matsuda, T.; Nakamura, H.; Ito, Y. *Tetrahedron* **1999**, *55*, 8787. (c) Da Silva, J. C. A.; Birot, M.; Pillot, J.-P.; Petraud, M. *J. Organomet. Chem.* **2002**, *646*, 179.

(5) Ohmura, T.; Oshima, K.; Taniguchi, H.; Suginome, M. *J. Am. Chem. Soc.* **2010**, *132*, 12194.

(6) (a) Gualco, P.; Ladeira, S.; Miqueu, K.; Amgoune, A.; Bourissou, D. *Angew. Chem., Int. Ed.* **2011**, *50*, 8320. (b) Joost, M.; Gualco, P.; Coppel, Y.; Miqueu, K.; Kefalidis, C. E.; Maron, L.; Amgoune, A.; Bourissou, D. *Angew. Chem., Int. Ed.* **2014**, *53*, 747.

(7) Lassauque, N.; Gualco, P.; Mallet-Ladeira, S.; Miqueu, K.; Amgoune, A.; Bourissou, D. *J. Am. Chem. Soc.* **2013**, *135*, 13827.

(8) Joost, M.; Gualco, P.; Mallet-Ladeira, S.; Amgoune, A.; Bourissou, D. *Angew. Chem., Int. Ed.* **2013**, *52*, 7160.

(9) Stratakis, M.; Garcia, H. *Chem. Rev.* **2012**, *112*, 4469.

(10) Gryparis, C.; Stratakis, M. *Chem. Commun.* **2012**, *48*, 10751.

(11) Gryparis, C.; Kidonakis, M.; Stratakis, M. *Org. Lett.* **2013**, *15*, 6038.

(12) We believe that the active catalytic sites are cationic gold species at the Au nanoparticle−metal oxide support interface region: (a) Fierro-Gonzalez, J. C.; Gates, B. C. *Chem. Soc. Rev.* **2008**, *37*, 2127. (b) Brown, M. A.; Fujimori, Y.; Ringleb, F.; Shao, X.; Stavale, F.; Nilius, N.; Sterrer, M.; Freund, H.-J. *J. Am. Chem. Soc.* **2011**, *133*, 10668. (c) Hong, S.; Rahman, T. S. *J. Am. Chem. Soc.* **2013**, *135*, 7629. (d) Wu, Y. Y.; Mashayekhi, N. A.; Kung, H. H. *Catal. Sci. Technol.* **2013**, *3*, 2881.

(13) $PhMe_2Si$-O-Bpin is chromatographically unstable but was undoubtedly characterized in crude reaction mixtures by comparison to known spectroscopic data: Kleeberg, C.; Cheung, M. S.; Lin, Z.; Marder, T. B. *J. Am. Chem. Soc.* **2011**, *133*, 19060. $PhMe_2Si$-O-Bpin is the main product in the attempted silaboration of alkynes catalyzed by Au/Al_2O_3 in nondried DCM (see the NMR spectra in page S11 of Supporting Information).

(14) (a) Tamao, K.; Hayashi, T.; Kumada, M. *J. Organomet. Chem.* **1976**, *114*, C19. (b) Suginome, M.; Oike, H.; Ito, Y. *J. Am. Chem. Soc.* **1995**, *117*, 1665.

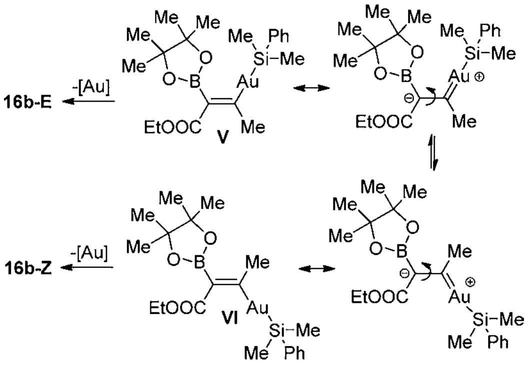
(15) Chenard, B. L.; van Zyl, C. M. *J. Org. Chem.* **1986**, *51*, 3561.

(16) General procedure for the Au/TiO_2-catalyzed silaboration of alkynes: To a vial containing the alkyne (0.2 mmol), $PhMe_2SiBpin$ (0.3 mmol), and 1 mL of DCM is added 40 mg of Au/TiO_2 (1.0 mol % in Au). After a certain period of time (see Table 1) at 25 °C, the reaction is complete (TLC, GC-MS). The slurry is filtered with the aid of DCM under low pressure through a short pad of silica gel or Celite, and the filtrate is evaporated to afford the silaboration products which are purified by column chromatography.

(17) A structurally similar 1,6-enyne also reacts with 1,1,3,3-tetramethyldisiloxane in the presence of Au/TiO_2 at surprisinly slow rate compared to other terminal alkynes: Kotzabasaki, V.; Lykakis, I. N.; Gryparis, C.; Psyllaki, A.; Vasilikogiannaki, E.; Stratakis, M. *Organometallics* **2013**, *32*, 665.

(18) In our hands, Au/TiO_2 does not catalyze hydroboration of alkynes with pinBH. Only homogeneous Au(I or III) catalysts are effective, yet in moderate yields: Leyva, A.; Zhang, X.; Corma, A. *Chem. Commun.* **2009**, 4947.

(19) The formation of (*Z*)-**16b** could be rationalized in terms of isomerization of intermediate V to VI, by analogy to the lack of stereoselectivity during the 1,2-disilylation of silyl-substituted acetylenes by σ disilanes.[11] MM2 calculations reveal that (*Z*)-**16b** is less stable than (*E*)-**16b** by ~2 kcal/mol.



(20) Psyllaki, A.; Lykakis, I. N.; Stratakis, M. *Tetrahedron* **2012**, *68*, 8724.

(21) Grirrane, A.; Corma, A.; Garcia, H. *Chem.—Eur. J.* **2011**, *17*, 2467.

(22) Chen, Q.; Zhao, J.; Ishikawa, Y.; Asao, N.; Yamamoto, Y.; Jin, T. *Org. Lett.* **2013**, *15*, 5766.

(23) Sakaki, S.; Biswas, B.; Musashi, Y.; Sugimoto, M. *J. Organomet. Chem.* **2000**, *611*, 288.