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Heterobimetallic Control of Regioselectivity in Alkyne Hydrostannylation: Divergent Syntheses of α- and (E)-β-Vinylstannanes via Cooperative Sn-H Bond Activation

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Supporting Information Placeholder

ABSTRACT: Cooperative Sn-H bond activation of hydrostannanes (Bu_3SnH) by tunable heterobimetallic (NHC)Cu-[M_{CO}] catalysts ([M_{CO}] = $FeCp(CO)_2$ or $Mn(CO)_5$) enables catalytic hydrostannylation of terminal alkynes under mild conditions, with Markovnikov/anti-Markovnikov selectivity controlled by the Cu/M pairing. By using the ^{Me}IMesCu-$FeCp(CO)_2$ catalyst, a variety of α-vinylstannanes were produced from simple alkyl-substituted alkynes and Bu_3SnH in high yield and good regioselectivity; these products are challenging to access by mononuclear metal-catalyzed hydrostannylation conditions. In addition, reversed regioselectivity was observed for aryl-substituted alkynes under the Cu/Fe-catalyzed conditions, affording the (E)-β-vinylstannanes as major products. On the other hand, by using the IMesCu-$Mn(CO)_5$ catalyst, a variety of (E)-β-vinylstannanes were produced from primary, secondary, and tertiary alkyl-substituted alkynes, thus demonstrating divergent regioselectivity for alkyne hydrostannylation controlled by Cu/Fe vs. Cu/Mn pairing. Both methods are amenable to gram-scale vinylstannane synthesis as well as late-stage hydrostannylation in a natural-product setting. Mechanistic experiments indicate *syn*-addition of Bu_3SnH to the alkynes and imply the involvement Sn-H bond activation in the rate-determining step. Two distinct catalytic cycles were proposed for the Cu/Fe and Cu/Mn catalysis based on the stoichiometric reactivity experiments.

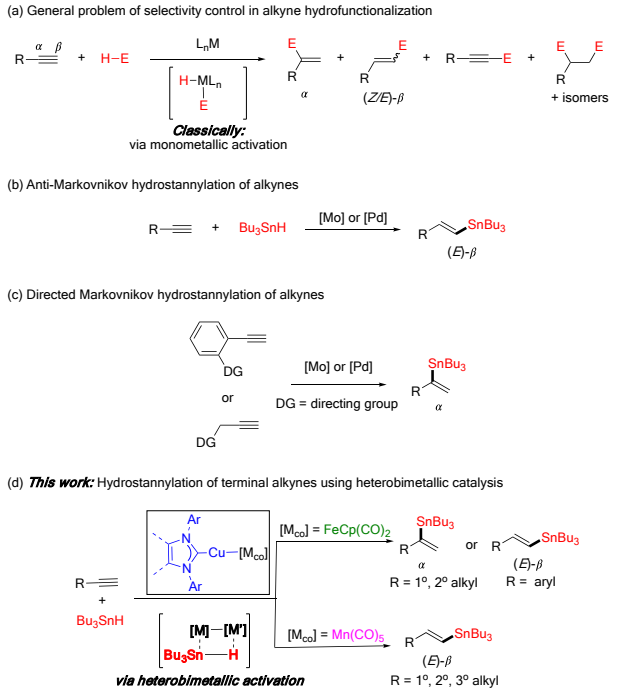
INTRODUCTION

Alkyne hydrofunctionalization represents a highly atom-economical approach for introducing synthetic functionality to a hydrocarbon functional group. The major challenge in alkyne hydrofunctionalization is the control of product selectivity, both with regard to Markovnikov vs. anti-Markovnikov regioselectivity and towards over-reduction or dehydrogenative coupling (Scheme 1a). A typical approach for developing selective hydrofunctionalization methods is to identify mononuclear metal catalysts capable of mediating the desired hydrofunctionalization, and then optimizing product selectivity through ligand design.[1] For cases where this classical approach has proven ineffective, it is worthwhile to consider alternative paradigms for catalyst design that provide new synthetic parameters with which to control selectivity.

As a case study, one can consider catalytic hydrostannylation of alkynes to produce vinylstannanes, which are of great important in synthetic chemistry due to their versatile transformations in many reactions,[2] especially the well-known Stille C-C cross-coupling reaction.[3] The development of efficient methods for the regio- and stereoselective preparation of vinylstannanes has been a major area of focus. A variety of catalysts based on e.g. Pd, Rh, and Mo have been employed in such transformations and display obvious advantages over radical-initiated processes in controlling regio- and stereoselectivity.[4] However, despite these advances, major voids still exist and motivate further catalyst development, particularly for controlling Markovnikov vs. anti-Markovnikov selectivity to produce either α- or β-vinylstananes selectively.[5] Thus far, most of reported methods lack generality by requiring alkynes bearing bulky or coordinating groups to enhance the regioselectivity.[6] While hydrostannylation of simple alkynes to produce (E)-β-vinylstananes selectively has been recently accomplished (Scheme 1b),[7] corresponding methods to provide α-vinylstananes selectively are underdeveloped. Current successful methods to synthesize α-vinylstananes from simple terminal alkynes either rely on the use of specialized tin hydride reagents (e.g. Bu_2SnIH),[8] or lose the desirable atom-efficiency of hydrofuncationalization by employing distannane, silylstannane,[9] or stannylmetallic reagents.[10] Known methods for adding readily available hydrostannanes such as Bu_3SnH directly to alkynes with Markovnikov

selectivity rely on substrate rather than catalyst control (Scheme 1c), such as exploiting directing effects for propargyl-functionalized alkynes[11] or aryl alkynes bearing *ortho*-substituents on the aromatic ring.[12] Therefore, the development of new strategies to enrich the hydrostannylation reaction and overcome the unsolved problem of approaching α-vinylstannanes from simple alkynes using R_3SnH reagents as the tin source is highly desirable.[13]

Scheme 1. Hydrostannylation of Terminal Alkynes

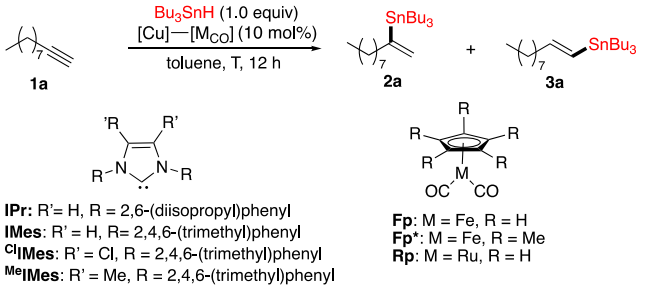


Bimetallic catalysis has emerged as an important strategy in synthetic chemistry, in particular by enabling different reactivity modes and/or selectivity patterns compared to conventional monometallic catalysis.[14] As bimetallic catalysis matures, it can increasingly be viewed as a tool to solve reactivity or selectivity problems that are challenging to solve with monometallic catalysis by harnessing these new bimetallic reactivity landscapes. Our group recently developed heterobimetallic catalysts consisting of copper carbene Lewis acids and metal carbonyl anion Lewis bases, i.e. (NHC)Cu-[M_{CO}],[15] wherein two metal sites within one catalyst could cooperatively activate H-Bpin or H-H bonds in catalytic scenarios through tunable bimetallic pairing.[16] Herein, we report that the tunable heterobimetallic (NHC)Cu-[M_{CO}] catalysts ([M_{CO}] = $FeCp(CO)_2$ or $Mn(CO)_5$) enable divergent syntheses of α- and (*E*)-β-vinylstannanes via catalytic hydrostannylation of terminal alkynes under mild conditions, with the selectivity being controlled by the Cu/M heterobimetallic pairing (Scheme 1d). Several aspects of this study make it both fundamentally important and also amenable to complex molecule synthesis. 1) The bimetallic catalyst can be easily generated *in situ* through salt metathesis between two readily-available pre-catalysts, (NHC)CuCl and Na[M_{CO}] or K[M_{CO}], which obviates additional steps for heterobimetallic catalyst preparation and makes optimization more efficient. 2) Both the α- and (*E*)-β-vinylstannanes can be accessed from a conserved heterobimetallic catalyst design. In particular, this has enabled us to develop the first general synthetic method to provide α-vinylstannanes from simple alkynes using Bu_3SnH as the tin source. 3) The use of cooperative bimetallic catalysis for hydrofunctionalization is conceptually novel and complements established monometallic catalysis4 and recently reported metal-ligand cooperativity in the dehydrogenative stannylation of alkynes.[17] Moreover, two distinct Sn-H bond activation modes are proposed to account for the divergent selectivity exhibited by the Cu/Fe and Cu/Mn catalysts.

RESULTS AND DISCUSSION

We began our work by studying the reaction between 1-decyne (**1a**) and Bu_3SnH using heterobimetallic complexes (NHC)Cu-[M_{CO}] formed *in situ* through salt metathesis between (NHC)CuCl and Na[M_{CO}] or K[M_{CO}] in toluene at room temperature.[15] The initial investigation of Na[M_{CO}] in the presence of IPrCuCl suggest that nucleophilicity of the metal carbonyl anion[18] is a very important parameter for this reaction. No product was found when the less nucleophilic metal carbonyl anions such as $[Co(CO)_4]^-$, $[CrCp(CO)_3]^-$, $[MoCp(CO)_3]^-$ and $[WCp(CO)_3]^-$ were used (Table 1, entry 1-4). Trace α- and (*E*)-β-vinylstannanes were detected with $[Mn(CO)_5]^-$. To our delight, the use of more nucleophilic $[RuCp(CO)_2]^-$ ($[Rp]^-$) and $[FeCp(CO)_2]^-$ ($[Fp]^-$) anions gave the α-vinylstannane **2a** selectively in 23% and 28% respectively (Table 1, entry 6-7). Next, we optimized the structure of NHC ligand to improve the reaction outcome: the yield of **2a** was largely enhanced when the IPr was replaced by IMes, and ^{Me}IMes turned out to be the optimal NHC ligand for this reaction (Table 1, entry 8-10). The use of $[FeCp^*(CO)_2]^-$ ($[Fp^*]^-$), which has similar nucleophilicity as $[Fp]^-$ but increased steric hindrance, gave a nearly same result (Table 1, entry 11). Control experiments demonstrated that both of the copper and iron partners were necessary for the reaction to occur (Table 1, entry 12-13). Better selectivity and yield were observed after lowering the temperature to 0 °C or -10 °C (Table 1, entry 14-15). In addition, increasing the loading of Bu_3SnH to 1.5 equivalents resulted in a slightly higher yield (Table 1, entry 16). Finally, we also found that use of excess ^{Me}IMesCuCl relative to KFp provides higher yields compared to equimolar co-catalyst loadings or with the pre-prepared ^{Me}IMesCu-Fp complex (Table 1, entry 17). We reasoned this might be due to an unstable organocopper intermediate during the catalytic cycle necessitating supplemental copper loading for optimal results.

Table 1. Optimizations for Synthesis of *α*-Vinylstannane[a]

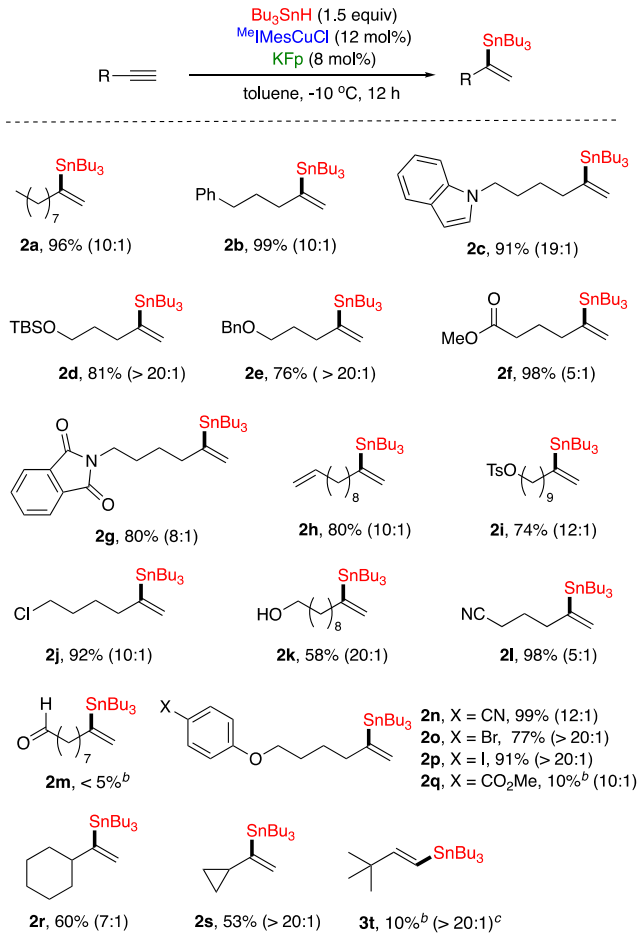


entry	[Cu]	[M_{CO}]	T (°C)	**2a** (%)	**3a** (%)
1	IPrCuCl	$NaCo(CO)_4$	rt	0	0
2	IPrCuCl	$NaCrCp(CO)_3$	rt	0	0
3	IPrCuCl	$NaMoCp(CO)_3$	rt	0	0
4	IPrCuCl	$NaMn(CO)_5$	rt	<5	6
5	IPrCuCl	$NaWCp(CO)_3$	rt	0	0
6	IPrCuCl	NaRp	rt	23	5
7	IPrCuCl	KFp	rt	28	8
8	IMesCuCl	KFp	rt	63	11
9	^{Cl}IMesCuCl	KFp	rt	47	28
10	^{Me}IMesCuCl	KFp	rt	67	14
11	^{Me}IMesCuCl	NaFp*	rt	67	15
12	--	KFp	rt	0	0
13	^{Me}IMesCuCl	--	rt	0	0
14	^{Me}IMesCuCl	KFp	0	70	11
15	^{Me}IMesCuCl	KFp	-10	75	8
16[b]	^{Me}IMesCuCl	KFp	-10	84	8
17[b,c]	^{Me}IMesCuCl	KFp	-10	**91**	**8**

[a] Reaction was performed on 0.1 mmol scale. Yields were determined by ^{1}H NMR integration of crude mixtures against an internal standard. [b]1.5 equiv. Bu_3SnH was used. [c]12 mol% ^{Me}IMesCuCl and 8 mol% KFp were used.

With the optimal conditions in hand, we next investigated the substrate scope of alkyl-substituted alkynes (Table 2). We were delighted to find that a variety of alkynes underwent hydrostannylation under our catalytic conditions to furnish *α*-vinylstannanes in high yields with good regioselectivity. Functional groups such as indolyl (**2c**), silyl ether (**2d**), benzyl ether (**2e**), ester (**2f**) and phthalimide (**2g**) were generally well tolerated. Terminal alkene (**2h**) was also compatible with the reaction conditions and the C=C double bond remains intact. (Pseudo)halide groups such as alkyl tosylates and chlorides were also found to be compatible (**2i**, **2j**). Remarkably, the reaction can also be conducted in the presence of an unprotected alcohol group (**2k**). Strongly coordinating alkyl nitriles (**2l**) and aryl nitriles (**2n**) had little effect on the results. Substrates bearing remote aryl bromide and aryl iodide linkages (**2n, 2o**) also worked well, providing potential synthetic handles for further coupling reactions. Trace product and low yield was found with the substrates bearing a remote aldehyde (**2m**) or aryl ester group (**2q**). Under the same reaction conditions, the substrate scope can be extended to cyclic alkyl-substituted alkynes, although the corresponding vinylstannanes (**2p**, **2q**) were obtained in moderate yield. Interestingly, reversed regioselectivity was observed when *tert*-butylethyne was used as substrate, although the (*E*)-*β*-vinylstannane (**3t**) was formed in poor yield. This behavior is possibly caused by the increased steric hindrance of the tertiary-alkyl substituent. Internal alkynes did not react under these conditions.

Table 2. Hydrostannylation of Alkyl-substituted Alkynes Using [Cu-Fe] catalyst[a]

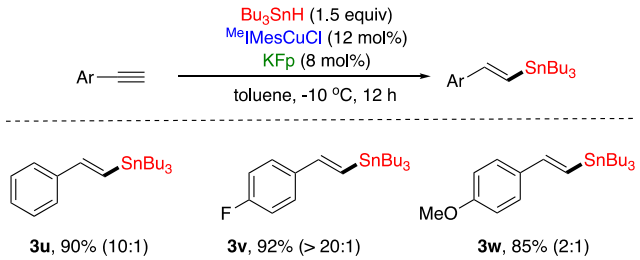


[a]The reaction was conducted on 0.2 mmol scale. All yields are isolated yields unless otherwise noted. The *α*/*β* ratios were determined by ^{1}H NMR from the isolated mixtures and are given in parentheses. [b]Yields were determined by ^{1}H NMR integration of crude mixtures against an internal standard. [c]Ratio of *β*/*α*.

Next, aryl-substituted alkynes were tested under the same reaction conditions (Table 3). Surprisingly, the (*E*)-*β*-vinylstannanes were observed as the major products. This outcome differs from that of previous Cu-catalyzed hydrostannylation of aryl-substituted alkynes using

hexamethyldistannane, where the α-vinylstannanes are generated as the major products.[9] We speculate the substantial steric hindrance of the aryl-substitute renders the -$SnBu_3$ group more likely add to the β position of the alkynes, whereas in previous report the use of the relative small -$SnMe_3$ group did not alter the regioselectivity. It is worthy to note similar reversed regioselectivity was also observed in the hydrostannylation of alkyl- or aryl-substituted alkynes using stoichiometric stannylcopper reagents.[19] Briefly investigating the substrate scope revealed that an electron-deficient aryl alkyne gave excellent yield and regioselectivity (**3v**), while poor regioselectivity was observed with an electron-rich aryl alkyne (**3w**).

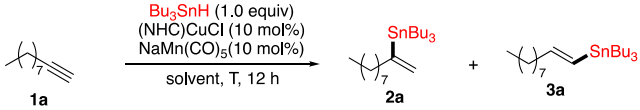
Table 3. Hydrostannylation of Aryl-substituted Alkynes Using [Cu-Fe] catalyst[a]



[a] The reaction was conducted on 0.2 mmol scale. All yields are isolated yields. The β/α ratios were determined by ^{1}H NMR from the isolated mixtures and are given in parentheses.

During the course of optimization, the (*E*)-β-vinylstannanes **3a** was observed in low yield as the major product when $NaMn(CO)_5$ instead of KFp was used as the partner with IPrCuCl (Table 1, entry 4). This result indicated that the reversed regioselectivity for hydrostannylation of terminal alkyl alkynes might be achieved by tuning one of the two metal sites within the bimetallic complex. Thus, we directed our efforts towards optimizing the formation of (*E*)-β-vinylstannanes **3a** (Table 4). Further investigation of other NHC ligands revealed the IMesCuCl greatly enhanced the yield and selectivity (Table 4, entry 2-4). Performing the reaction at higher temperature (60 °C) could speed up the reaction and led to a higher yield of **3a** (Table 4, entry 5). In addition, increasing the amount of Bu_3SnH to 1.2 equivalent resulted in a slightly increased yield (Table 4, entry 6). While other solvents such as benzene, 1,4-dioxane and THF gave similar result as toluene (Table 4, entry 7-9), we were delighted to find use of DCE afforded the (*E*)-β-vinylstannanes **3a** in both higher yield and better selectivity (Table 4, entry 10).

Table 4. Optimizations for Synthesis of (*E*)-β-Vinylstannane[a]

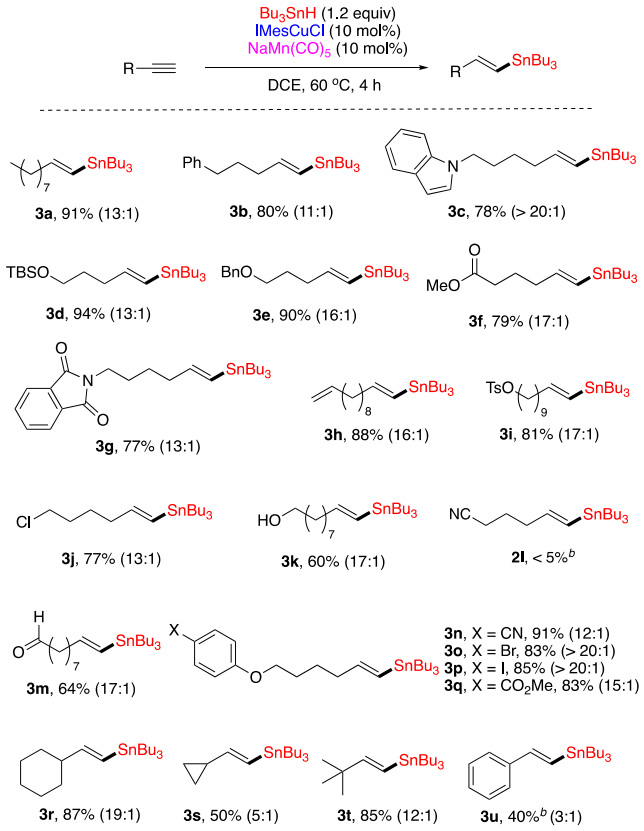


entry	(NHC)CuCl	solvent	T (°C)	**2a** (%)	**3a** (%)
1	IPrCuCl	toluene	rt	<5	6
2	IMesCuCl	toluene	rt	5	79
3	^{Cl}IMesCuCl	toluene	rt	7	79
4	^{Me}IMesCuCl	toluene	rt	6	72
5	IMesCuCl	toluene	60	10	86
6[b]	IMesCuCl	toluene	60	10	90
7[b]	IMesCuCl	benzene	60	12	88
8[b]	IMesCuCl	1,4-dioxane	60	11	89
9[b]	IMesCuCl	THF	60	11	89
10[b]	IMesCuCl	DCE	60	**7**	**93**

[a] Reaction was performed on 0.1 mmol scale. Yields were determined by ^{1}H NMR integration of crude mixtures against an internal standard. [b]1.2 equiv. Bu_3SnH was used and the reaction time is 4 h.

Under the optimal conditions, a range of alkynes bearing different functional groups were investigated (Table 5). Almost all the alkynes tested in [Cu-Fe] catalysis smoothly underwent anti-Markovnikov Bu_3SnH addition under [Cu-Mn]-catalyzed conditions to afford (*E*)-β-vinylstannanes in high yields with good regioselectivity. The remote aldehyde (**3m**) and aryl ester groups (**3q**) that were not tolerated in the [Cu-Fe] system were found to be compatible with the [Cu-Mn] system. While an arylcyano group (**3n**) has no effect on the reaction, a remote alkylcyano group (**2l**) led to only trace product. Under the same reaction conditions, the substrate scope can be extended to include secondary and even tertiary alkyl alkynes (**3t**), the latter of which was unsuccessful in the [Cu-Fe] catalysis. Unfortunately, moderated yield and selectivity were obtained with phenyl acetylene (**3u**).

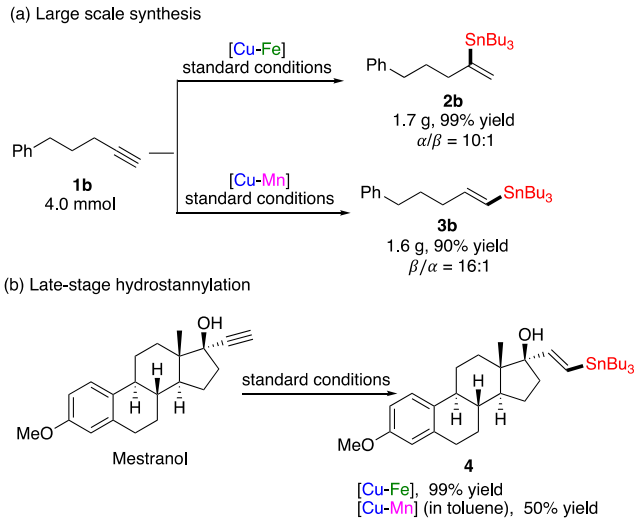
Table 5. Hydrostannylation of Alkyl-substituted Alkynes Using [Cu-Mn] catalyst[a]



[a]The reaction was conducted on 0.2 mmol scale. All yields are isolated yields. The *β*/*α* ratios were determined by ^{1}H NMR from the isolated mixtures and are given in parentheses. [b]Yields were determined by ^{1}H NMR integration of crude mixtures against an internal standard.

To demonstrate the practical utility of this methodology, we performed the reaction on large scale. Under the standard reaction conditions established for [Cu-Fe] and [Cu-Mn] catalysis, use of 4 mmol of **1b** allowed for isolation of 1.7 g of *α*-vinylstannane **2b** and 1.6 g of (*E*)-*β*-vinylstannane **3b**, respectively, while maintaining high reactivity and regioselectivity (Scheme 2a). Moreover, the mild reaction conditions provide the opportunity for late-stage hydrostannylation of natural products or drugs. For example, when Mestranol, an estrogen medication used in birth control pills, was subjected to the two reaction conditions, the (*E*)-*β*-vinylstannane **4** was obtained as a single isomer in excellent yield under the [Cu-Fe] catalytic conditions, whereas moderate yield was observed under the [Cu-Mn] catalytic conditions using the toluene as solvent (Scheme 2b).

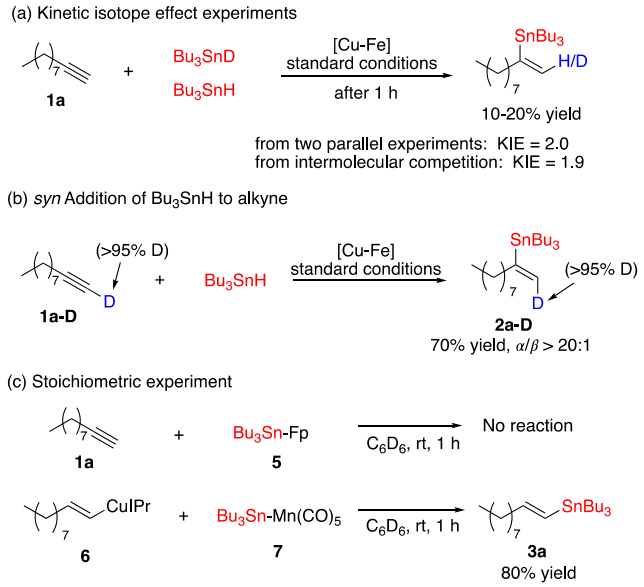
Scheme 2. Synthetic Utility



Next, some experiments were conducted to explore the mechanism of bimetallic catalysis. Kinetic isotope effect (KIE) experiments were performed using Bu_3SnH and Bu_3SnD in the [Cu-Fe] catalysis. In these experiments, the reaction was quenched after 1 h by addition of Et_3N. The KIE value was calculated to be 2.0 and 1.9 from parallel and competition experiments, respectively (Scheme 3a). In addition, a relative rate of 1.0 was found in two parallel experiments using **1a** and **1a-D** with Bu_3SnH (see Supporting Information). These results strongly suggest the involvement of Sn-H activation in the rate-determining step during bimetallic catalysis. For [Cu-Mn] catalysis, the selective formation of (*E*)-*β*-vinylstannanes clearly demonstrates the *syn* addition of the Bu_3SnH to alkynes. For [Cu-Fe] catalysis, deuterated alkyne **1a-D** was synthesized and subjected to hydrostannylation catalyzed (Scheme 3b). The *E*-isomer **2a-D** was selectively formed, which demonstrates that *syn* addition of Bu_3SnH to the alkyne also occurs under the [Cu-Fe] catalytic conditions. This result also indicates that formation of a copper acetylide intermediate is unlikely because no occurrence of H/D exchange from **1a-D** and Bu_3SnH was observed. To further probe the activation modes by two different bimetallic catalysts, we conducted stoichiometric experiments. For [Cu-Fe] catalysis, according to the previous literatures involving the stannylcupration of alkynes,[20] we assume a [Cu]-$SnBu_3$ intermediate is generated upon the activation of Bu_3SnH. However, our attempts to prepare (NHC)Cu-$SnBu_3$ via many methods failed, producing Bu_3Sn-$SnBu_3$ as a decomposition product in the absence of alkyne substrate. Nevertheless, we found no reaction occurred between Bu_3Sn-Fp or Fp*-H and 1-decyne. These results may exclude the [Fe] partner interacting with the alkynes and necessity the role of [Cu]-$SnBu_3$. On the other hand, we prepared the alkenylcopper **6** from the addition of the [Cu]-H to 1-decyne. The alkenylcopper **6** readily reacted with the Bu_3Sn-$Mn(CO)_5$ at the room temperature to give the *β*-vinylstannanes as a single product in 80% yield. These results support the intermediacy of (NHC)Cu-H

and Bu_3Sn-$Mn(CO)_5$ in the activation of Bu_3SnH by the [Cu-Mn] catalyst.

Scheme 3. Mechanistic Studies



Based on the above experiments combined with our previous work, two distinct mechanisms were proposed for [Cu-Fe] and [Cu-Mn] catalysis (Scheme 4). For the [Cu-Fe] catalyst, Bu_3Sn-H activation forms protic [Fe]-H **B** and Bu_3Sn-[Cu] **C**. Then, *syn* addition of **C** to alkyl-substituted terminal alkynes affords the *α*-stannylalkenylcopper **D**.[20] Finally, protonolysis of complex **D** by [Fe]-H **B** gives the *α*-vinylstannanes and regenerates the bimetallic catalyst. For aryl-substituted alkynes, we hypothesize that the formation of *β*-stannylalkenylcopper **D'** was favored due to the increased steric hindrance of the aryl substituent, thus leading to the *β*-vinylstannane product after protonolysis by **B**. For the [Cu-Mn] system, we instead propose that Bu_3Sn-H activation forms Bu_3Sn-[Mn] **F** and [Cu]-H **G** intermediates. The addition of the [Cu]-H **G** to the alkyne gives alkenylcopper **H**, which reacts with the **F** to deliver the (*E*)-*β*-vinylstannanes and regenerate the bimetallic catalyst. At this time, we do not have a clear understanding of the factors that control the divergent Sn-H activation behavior of catalysts **A** and **E**, and further experimental and computational studies probing this issue are underway.

SUMMARY

In summary, we have developed an unprecedented procedure for divergent synthesis of the *α*-vinylstannanes and (*E*)-*β*-vinylstannanes via hydrostannyaltion of terminal alkynes mediated by a tunable heterobimetallic catalysts. By using ^{Me}IMesCu-FeCp$(CO)_2$ as a catalyst, a variety of *α*-vinylstannanes can be synthesized in high yield and good selectivity under mild reaction conditions. This protocol represents the first general synthetic method for preparation of *α*-vinylstannanes from simple alkyl-substituted alkynes using readily available Bu_3SnH as the tin source. In addition, reversed regioselectivity was found for aryl-substituted alkynes, affording the (*E*)-*β*-vinylstannanes as major products. Further investigation of heterobimetallic catalysts revealed IMesCu-$Mn(CO)_5$ was an efficient catalyst for synthesis of (*E*)-*β*-vinylstannanes. Primary, secondary and tertiary alkyl-substituted alkynes are all applicable under the reaction conditions. The utility of this method was demonstrated by the large-scale synthesis of vinylstannanes and by late-stage hydrostannylation of Mestranol. Mechanistic experiments supported the *syn* addition of Bu_3SnH to the alkynes and indicated the involvement Sn-H bond activation in the rate-determining step. Two distinct Sn-H bond activation modes were proposed based on the stoichiometric experiments. In the [Cu-Fe] catalytic cycle, [Cu]-$SnBu_3$ and protic [Fe]-H were likely formed upon the activation of Bu_3SnH; however, the selectivity was reversed in the [Cu-Mn] catalytic cycle, where [Cu]-H and [Mn]-$SnBu_3$ were likely generated as the key intermediates. This divergent reactivity with Bu_3SnH is the source of the heterobimetallic control of regioselectivity.

ASSOCIATED CONTENT

Supporting Information. The Supporting Information is available free of charge on the ACS Publications website. Experimental procedures & spectral data (PDF)

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REFERENCES

[1] (a) Yadav, J. S.; Antony, A.; Rao, T. S.; Reddy, B. V. S. Recent progress in transition metal catalyzed hydrofunctionalization of less activated olefins. *J. Organomet. Chem.* **2011**, *696*, 16. (b) Ananikov, V. P.; Tanaka, T. Hydrofunctionalization, Springer, Heidelberg, **2013**. (c) Zheng, Y.; Zi, W. Transition-metal catalyzed enantioselective hydrofunctionalization of alkynes. *Tetrahedron Lett.* **2018**, *59*, 2205. (d) Chen, J.; Guo, J.; Lu, Z. Recent Advances in Hydrometallation of Alkenes and Alkynes via the First Row Transition Metal Catalysis. *Chin. J. Chem*. **2018**, *36*, 1075.

[2] (a) Pereyre, M. Quintard, J.-P. Rahm, A. *Tin in Organic Synthesis;* Butterworths: London, **1987**; (b) Main Group Metals in Organic Synthesis, Vol. 1, 2 (Eds.: H. Yamamoto, K. Oshima), Wiley-VCH, Weinheim, **2004**.

[3] Farina, V.; Krishnamurthy, V.; Scott, W. J. *The Stille Reaction*; Wiley: New York, **2004**.

[4] For reviews of hydrostannylation reactions, see (a) Yoshida, H. Stannylation Reactions under Base Metal Catalysis: Some Recent Advances. *Synthesis* **2016**, *48*, 2540. (b) Trost, B. M.; Ball, Z. T.

Addition of Metalloid Hydrides to Alkynes: Hydrometallation with Boron, Silicon, and Tin. *Synthesis* **2005**, 853. (c) Smith, N. D.; Mancuso, J.; Lautens, M. Metal-Catalyzed Hydrostannations. *Chem. Rev*. **2000**, *100*, 3257.

[5] See ref 3 and the follow example: Rice, M. B.; Whitehead, S. L.; Horvath, C. M.; Muchnij, J. A.; Maleczka, R. E., Jr. The Regiochemical Influence of Oxo-Substitution in Palladium-Mediated Hydrostannations of 1-Alkynes. *Synthesis* **2001**, 1495.

[6] For selected examples, see: (a) Ichinose, Y. Oda, H. Oshima, K. Utimoto, K. Palladium Catalyzed Hydrostannylation and Hydrogermylation of Acetylenes. *Bull. Chem. Soc. Jpn*. **1987**, *60*, 3468. (b) Zhang, H. X. Guibÿ, F. Balavoine, G. Palladium Catalyzed Hydrostannation of Alkynes and Palladium-Catalyzed Hydrostannolysis of Propargyl or Propargyloxycarbonyl Derivatives of Various Functional Groups. *Tetrahedron Lett*. **1988**, *29*, 619. (c) Zhang, H. X.; Guibe, F.; Balavoine, G. Palladium- and Molybdenum-Catalyzed Hydrostannation of Alkynes. A Novel Access to Regio- and Stereodefined Vinylstannanes. *J. Org. Chem*. **1990**, *55*, 1857. (d) Maleczka, R. E. Jr.; Ghosh, B.; Gallagher, W. P.; Baker, A. J.; Muchnij, J. A.; Szymanski, A. L. Non-Pd Transition Metal-catalyzed Hydrostannations: Bu_3SnF/PMHS as a Tin Hydride Source. *Tetrahedron* **2013**, *69*, 4000.

[7] (a) Darwish, A.; Lang, A.; Kim, T.; Chong, J. M. The Use of Phosphine Ligands to Control the Regiochemistry of Pd-Catalyzed Hydrostannations of 1-Alkynes: Synthesis of (E)-1-Tributylstannyl-1-alkenes. *Org. Lett,* **2008**, *10*, 861. (b) Oderinde, M. S.; Froese, R. D. J.; Organ, M. G. 2,2'-Azobis(2-methylpropionitrile)-Mediated Alkyne Hydrostannylation: Reaction Mechanism. *Angew. Chem. Int. Ed.* **2013**, *52*, 11334. (c) Gupta, S.; Do, Y.; Lee, J. H.; Lee, M.; Han, J.; Rhee, Y. H.; Park, J. Novel Catalyst System for Hydrostannation of Alkynes. *Chem. Eur. J*. **2014**, *20*, 1267. (d) Mandla, K. A. Moore, C. E. Rheingold, A. L. Figueroa, J. S. Regioselective Formation of (E)-*β*-Vinylstannanes with a Topologically Controlled Molybdenum-Based Alkyne Hydrostannation Catalyst. *Angew. Chem. Int. Ed*. **2018**, *57*, 6853.

[8] Shibata, I.; Suwa, T.; Ryu, K.; Baba, A. Selective *α*-Stannylated Addition of Di-*n*-butyliodotin Hydride Ate Complex to Simple Aliphatic Alkynes. *J. Am. Chem. Soc*. **2001**, *123*, 4101.

[9] Yoshida, H.; Shinke, A.; Kawanoa Y.; Takakia, K. Copper-Catalyzed *α*-Selective Hydrostannylation of Alkynes for the Synthesis of Branched Alkenylstannanes. *Chem. Commun*. **2015**, *51*, 10616.

[10] (a) Hibino, J.; Matsubara, S.; Morizawa, Y.; Oshima, K.; Nozaki, H. Regioselective Stannylmetalation of Acetylenes in the Presence of Transition-metal Catalyst. *Tetrahedron Lett*. **1984**, *25*, 2151; (b) Matsubara, S.; Hibino, J.; Morizawa, Y.; Oshima, K.; Nozaki, H. Regio- and Stereo-selective Synthesis of Vinylstannanes. Transition-metal Catalyzed Stannylmetalation of Acetylenes and Conversion of Enol Triflates and Vinyl Iodides into Vinylstannanes. *J. Organomet. Chem*. **1985**, *285*, 163; (c) Sharma, S.; Oehlschlager, A. C. Control of Regiochemistry in Bismetallation of 1-Decyne. *Tetrahedron Lett.* **1986**, *27*, 6161; (d) Sharma, S.; Oehlschlager, A. C. Regioselective Synthesis and Cross Coupling Reactions of 1,2-Borostannyl-1-alkenes. *Tetrahedron Lett*. **1988**, *29*, 261; (e) Sharma, S.; Oehlschlager, A. C. Scope and Mechanism of Stannylalumination of 1-Alkynes. *J. Org. Chem.* **1989**, *54*, 5064.

[11] (a) Kazmaier, U.; Schauss, D.; Pohlman, M. $Mo(CO)_3(CN\text{-}t\text{-}Bu)_3(MoBI_3)$, a New Efficient Catalyst for Regioselective Hydrostannations. *Org. Lett*. **1999**, *1*, 1017; (b) Kazmaier, U.; Pohlman, M.; Schauß, D. Regioselective Hydrostannations with $Mo(CO)_3(CN^tBu)_3$ ($MoBI_3$) as a New, Efficient Catalyst. *Eur. J. Org. Chem.* 2000, 2761; (c) Braune, S.; Kazmaier, U. Regioselective Hydrostannations Catalyzed by Molybdenum Isonitrile Complexes. *J. Organomet. Chem*. **2002**, *641*, 26; (d) Braune, S.; Pohlman, M.; Kazmaier, U. Molybdenum-Catalyzed Stannylations as Key Steps in Heterocyclic Synthesis. *J. Org. Chem*. **2004**, *69*, 468; (e) Lin, H.; Kazmaier, U. Regioselective Mo-Catalyzed Hydrostannations as Key Steps in the Synthesis of Functionalized Amino Alcohols and Heterocycles. *Eur. J. Org. Chem.* **2007**, 2839; (f) Jena, N.; Kazmaier, U. Synthesis of Stannylated Allyl- and Vinylphosphonates via Molybdenum-Catalyzed Hydrostannations. *Eur. J. Org. Chem.* **2008**, 3852. (g) Lin, H.; Kazmaier, U. Molybdenum-Catalyzed α-Hydrostannations of Propargylamines as the Key Step in the Synthesis of N-Heterocycles. *Eur. J. Org. Chem*. **2009**, 1221.

[12] Hamze, A.; Veau, D.; Provot, O.; Brion, J.-D.; Alami, M. Palladium-Catalyzed Markovnikov Terminal Arylalkynes Hydrostannation: Application to the Synthesis of 1,1-Diarylethylenes. *J. Org. Chem*. **2009**, *74*, 1337.

[13] For a relevant report with only 3 demonstrated examples, see: Rummelt, S. M.; Fürstner, A. Ruthenium-Catalyzed trans-Selective Hydrostannation of Alkynes. *Angew. Chem. Int. Ed*. **2014**, *53*, 3626.

[14] (a) Kamijo, S.; Yamamoto, Y. In Multimetallic Catalysts in Organic Synthesis; Shibasaki, M., Yamamoto, Y., Eds.; Wiley-VCH: New York, **2004**; Chapter 1. (b) D. C. Powers, T. Ritter, Bimetallic Redox Synergy in Oxidative Palladium Catalysis. *Acc. Chem. Res.* **2012**, *45*, 840. (c) N. P. Mankad, Selectivity Effects in Bimetallic Catalysis. *Chem. Eur. J.* **2016**, *22*, 5822; (d) D. R. Pye, N. P. Mankad, Bimetallic catalysis for C–C and C–X coupling reactions. *Chem. Sci*. **2017**, *8*, 1705; (e) I. G. Powers, C. Uyeda, Metal−Metal Bonds in Catalysis. *ACS Catal.* **2017**, *7*, 936.

[15] Banerjee, S.; Karunananda, M. K.; Bagherzadeh, S.; Jayarathne, U.; Parmelee, S. R.; Waldhart, G. W.; Mankad, N. P. Synthesis and Characterization of Heterobimetallic Complexes with Direct Cu–M Bonds (M = Cr, Mn, Co, Mo, Ru, W) Supported by N-Heterocyclic Carbene Ligands: A Toolkit for Catalytic Reaction Discovery. *Inorg. Chem*. **2014**, *53*, 11307.

[16] For our group's work on heterobimetallic catalysis, see: (a) Mazzacano, T. J.; Mankad, N. P. Base Metal Catalysts for Photochemical C-H Borylation That Utilize Metal-Metal Cooperativity. *J. Am. Chem. Soc*. **2013**, *135*, 17258. (b) Karunananda, M. K.; Mankad, N. P. E-Selective Semi-Hydrogenation of Alkynes by Heterobimetallic Catalysis. *J. Am. Chem. Soc*. **2015**, *137*, 14598. (c) Bagherzadeh, S.; Mankad, N. P. Catalyst Control of Selectivity in CO_2 Reduction Using a Tunable Heterobimetallic Effect. *J. Am. Chem. Soc.* **2015**, *137*, 10898. (d) Pye, D. R.; Mankad, N. P. Cu/Mn Bimetallic Catalysis Enables Carbonylative Suzuki-Miyaura Coupling with Unactivated Alkyl Electrophiles. *Chem. Sci*. **2017**, *8*, 4750. For a recent account, see: (e) Mankad, N. P. Selectivity Effects in Bimetallic Catalysis. *Chem. Commun.* **2018**, *54*, 1291.

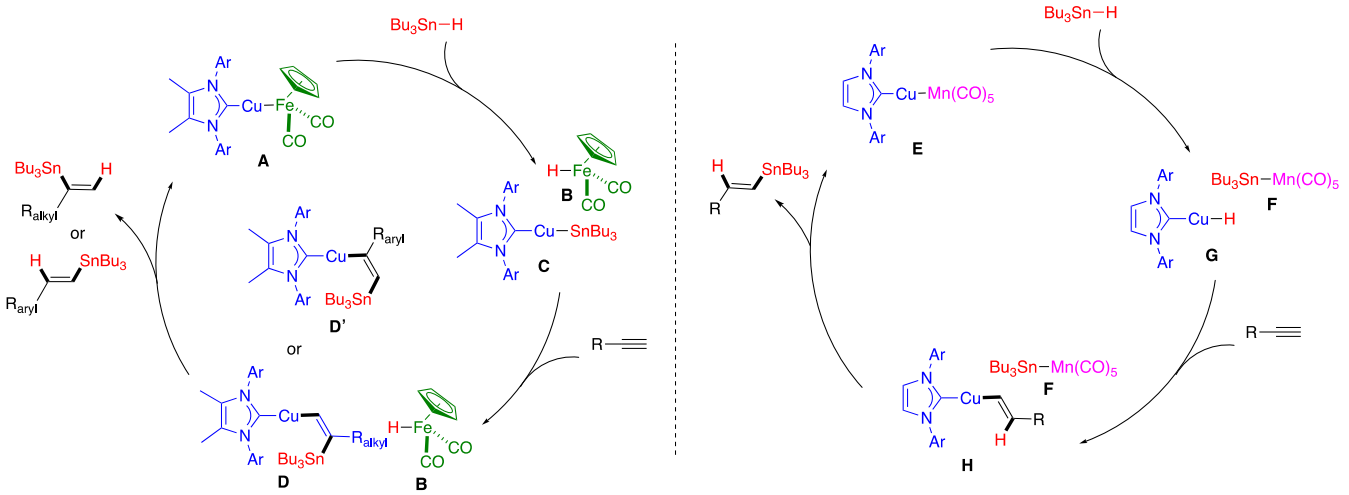
[17] Forster, F.; Lopez, V. M. R.; Oestreich, M. Catalytic Dehydrogenative Stannylation of C(sp)–H Bonds Involving Cooperative Sn–H Bond Activation of Hydrostannanes. *J. Am. Chem. Soc*. **2018**, *140*, 1259.

[18] King, R. B. Some Applications of Metal Carbonyl Anions in the Synthesis of Unusual Organometallic Compounds. *Acc. Chem. Res*. **1970**, *3*, 417.

[19] (a) Barbero, A.; Cuadrado, P.; Fleming, I.; González, A. M.; Pulido, F. J. The Stannyl-Cupration of Acetylenes and the Reaction of the Intermediate Cuprates with Electrophiles as a Synthesis of Substituted Vinylstannanes. *J. Chem. Soc., Chem. Commun*. **1992**, 351. (b) Barbero, A.; Cuadrado, P.;Fleming, I.; González, A. M.; Pulido, F. J.; Rubio, R. Stannyl-cupration of Acetylenes and the Reaction of the Intermediate Cuprates with Electrophiles as a Synthesis of Substituted Vinylstannanes. *J. Chem. Soc., Perkin Trans.1,* **1993**, 1657. (c) Barbero A.; Pulido, F. J. Allylstannanes and Vinylstannanes from Stannylcupration of C–C Multiple Bonds. Recent Advances and Applications in Organic Synthesis. *Chem. Soc. Rev*. **2005**, *34*, 913.

[20] Singer, R. D.; Hutzzinger, M. W.; Oehlschlager, A. C. Additions of CuCN-Derived Stannylcuprates to Terminal Alkynes: A Comparative Spectroscopic and Chemical Study. *J. Org. Chem.* **1991**, *56*, 4933.

Scheme 4. Proposed mechanisms for heterobimetallic alkyne hydrostannylation.



TOC graphic: