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A Drastic Effect of TEMPO in Zinc-Catalyzed Stannylation of Terminal Alkynes with Hydrostannanes via Dehydrogenation and Oxidative Dehydrogenation

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Abstract: With a system consisting of a catalytic zinc Lewis acid, pyridine, and TEMPO in a nitrile medium, terminal alkynes coupled with $HSnBu_3$, providing alkynylstannanes with structural diversity. The resulting alkynylstannane, without being isolated, could be directly used for Pd- and Cu-catalyzed transformations to deliver internal alkynes and more intricate tin-atom-containing molecules. Mechanistic studies indicated that $TEMPOSnBu_3$ formed in situ from TEMPO and $HSnBu_3$ works to stannylate the terminal alkyne in collaboration with the zinc catalyst, and that both of dehydrogenation and oxidative dehydrogenation processes are uniquely involved in a single reaction.

Keywords: Alkynes; Dehydrogenation; Lewis acids; Tin; Zinc

Introduction

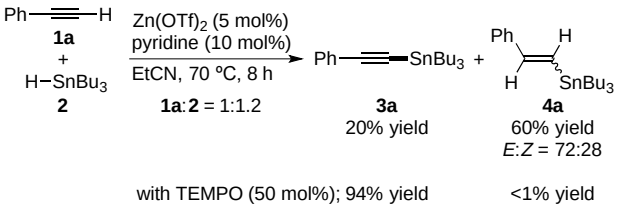
Organostannanes are a useful class of organometallic compounds, due to their wide spectrum of applications, including industrial, agricultural, biological, and synthetic uses.[1] Alkynylstannanes, which can be converted to various targets, have also been used as organometallic reagents.[2,3] The synthetic advantage of organostannanes involving alkynylstannanes would be ascribed to a good balance of the reactivity and stability like no others. For example, bench-stable alkynylstannanes participate in the Kosugi–Migita–Stille cross-coupling (KMSCC) reaction without external activators.[4] The most common way to obtain alkynylstannanes consists of the following two stages: deprotonation of terminal alkynes with strong metallic bases, such as BuLi[5a] and $(Me_3Si)_2NLi$,[5b] and a subsequent treatment of the resulting alkynylmetals with tin halides. This strategy, however, requires handling of the moisture-sensitive reagents, and also coproduces stoichiometric wastes of metal salts and protonated bases. Moreover, the base-sensitive functionalities are incompatible with this strategy. Terminal alkynes have also been known to undergo stannylation with distannoxanes,[6] tin amides,[7] tin cyanides,[8] and tin methoxides.[9] Among the methods, the stannylation with the tin methoxide reported by the Yasuda–Baba group is likely to be the most user-friendly, in view of the functional group compatibility, reagent usability, and only MeOH waste.

On the other hand, making a molecular structure via dehydrogenation[10] or oxidative dehydrogenation[11] has attracted substantial attention in the last couple of decades. This would be due to requiring no time-consuming pre-introduction of reactive functional groups. In this regard, we have disclosed that, under zinc–pyridine catalysis in a nitrile medium, alkynyl C–H bonds couple with H–*Si*[12] and H–B(dan)[13] (dan = 1,8-diaminonaphtyl) in a dehydrogenative fashion. The importance of our original zinc–pyridine–nitrile system is that all inexpensive commercial sources including the zinc Lewis acid based on an abundant metal resource in nature are available, in contrast to the general types catalyzed by rare, and thus, expensive transition metals. To date, despite the well-studied dehydrogenative C–Si[14,15] and C–B[16,17] bond-forming couplings, the stannylation thereof has only two precedents for the alkynyl C–H bond, once again, with transition metal catalysts of Rh[18] and Ru.[19] We herein report on the first case of non-transition-metal-catalyzed stannylation of alkynes with hydrostannanes, and also clarify that a unique reaction mechanism is operative.

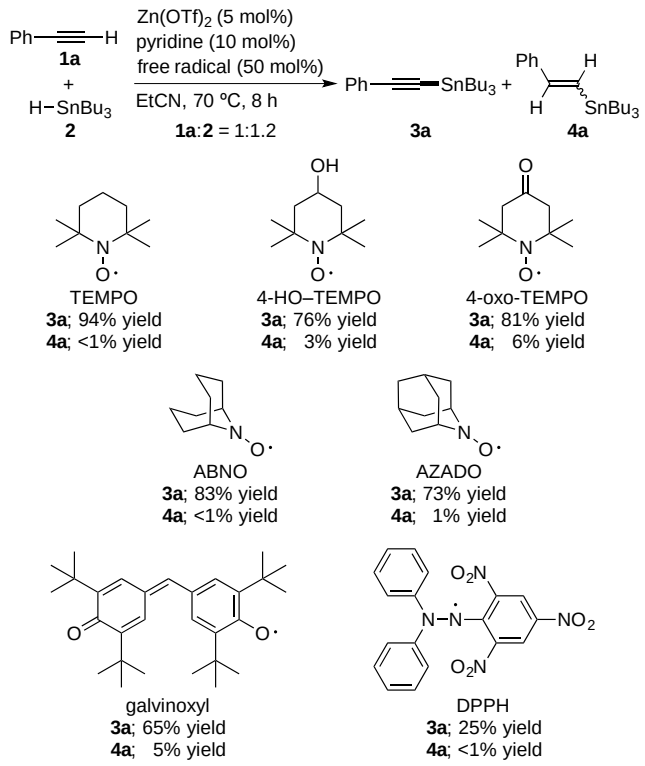
Results and Discussion

10.1002/adsc.201900540

We began this study by evaluating whether our system works for the reaction of PhC≡CH (**1a**) with $HSnBu_3$ (**2**) (Scheme 1). Thus, the treatment of **1a** and **2** with $Zn(OTf)_2$ (Tf = SO_2CF_3; 5 mol%) and pyridine (10 mol%) in EtCN at 70 °C for 8 h provided tributyl(phenylethynyl)tin (**3a**) in 20% yield, but with a considerable amount of undesired hydrostannylation products **4a** as an *E*/*Z* mixture (72:28). Radical-induced hydrostannylation of **1a** with **2** has been reported to predominantly yield *E*-**4a**,[20] implying that the *E*-enrichment in Scheme 1 is likely to be due to the involvement of a radical species. To confirm this conjecture and also to reduce the radical influence, the reaction was conducted in the presence of 2,2,6,6-tetramethylpiperidine 1-oxyl (TEMPO; 50 mol%) known as a radical scavenger. Beyond our expectation, the formation of **4a** was completely suppressed, and, instead, the efficiency of the desired route was drastically improved, giving **3a** as a sole product in 94% NMR yield. Inspired by this result, the effect of



Scheme 1. Effect of TEMPO in Zn-catalyzed stannylation of PhC≡CH with $HSnBu_3$. Averages of yields determined by ^1H and ^{119}Sn NMR are shown here.

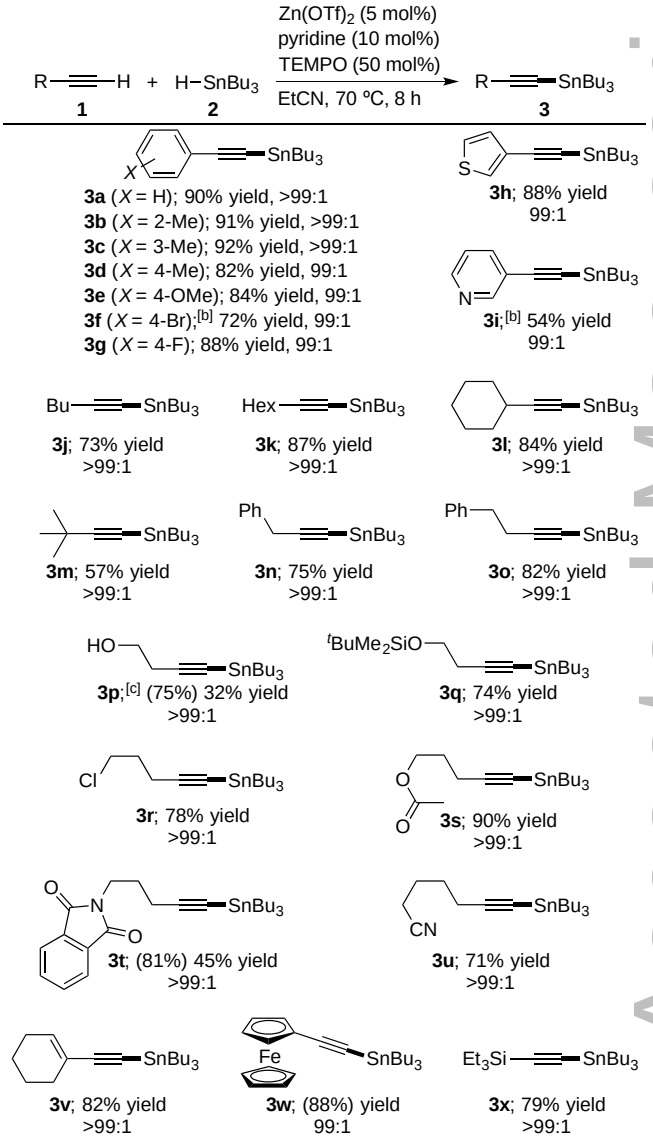


Scheme 2. Effect of free radicals in Zn-catalyzed stannylation of PhC≡CH with $HSnBu_3$. Averages of yields determined by ^1H and ^{119}Sn NMR are shown here.

other free radicals, such as TEMPO analogs as well as galvinoxyl and 2,2-diphenyl-1-picrylhydrazyl (DPPH), was investigated (Scheme 2). All of these effectively suppressed the route for **4a**, but, as a result, TEMPO proved to be the most suitable choice in terms of both the yield and selectivity of **3a**.

With the promising reaction conditions in hand, we explored the scope of alkynes in the reaction (Table 1). Besides **1a**,[21] aryl alkynes with different steric and electronic natures reacted successfully with **2** to afford alkynylstannanes **3a**–**3g** in high yields. Heteroaryl alkynes with the electron-rich thienyl ring and the electron-poor pyridyl ring participated well in this strategy (**3h**, **3i**). A series of aliphatic alkynes having

Table 1. Zn-catalyzed stannylation of terminal alkynes with $HSnBu_3$.[a]



[a] Reagents (unless otherwise noted): **1** (0.40 mmol), **2** (0.48 mmol), $Zn(OTf)_2$ (20 μmol), pyridine (40 μmol), TEMPO (0.20 mmol), EtCN (0.40 mL). Yields of isolated **3** based on **1** are shown here. Averages of yields determined by ^1H and ^{119}Sn NMR are given in parentheses. Ratios of **3**:**4** determined by ^{119}Sn NMR are shown after yields. [b] Performed with TEMPO (0.30 mmol). [c] Performed with **2** (0.96 mmol) and TEMPO (0.40 mmol).

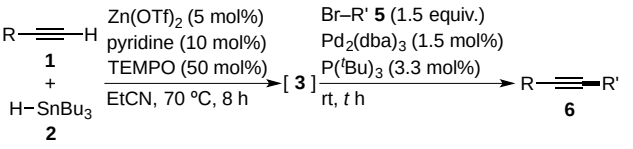
primary, secondary, and tertiary alkyl groups with or without a functional group underwent stannylation as well, thereby giving **3j**–**3u** in good to high yields. The C=C bond of **1v** was tolerated without suffering hydrostannylation.[22] The stannylation of **1w** with the ferrocenyl group gave **3w**, which is reportedly useful to make, for instance, a photo-switching material.[23] Silylethynyltin **3x** with the two transformable units for further elaboration can also be obtained. The results in Table 1 reveal accordingly that 1) various functional groups involving Br–C(sp^2), F–C(sp^2), pyridyl, HO–C_2H_4, ^{t}BuMe$_2$SiO, Cl–C(sp^3), acetoxy, phthalimidoyl, NC, C=C, ferrocenyl, and Et$_3$Si are compatible with this method [note: despite the successful coupling of **1p** with the OH group, propargyl alcohol ($HOCH_2C{\equiv}CH$) failed to react with **2**.]; 2) excellent selectivity of the stannylation over the hydrostannylation is always achievable.

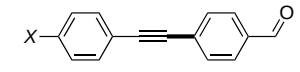
There is an additional note to be aware of when isolating products **3**. Due to their decomposition on silica gel, yet having good thermal stability,[9] distillation will be the most suitable way to purify **3**; in fact, almost all **3** in Table 1 were distilled safely in pure form (see Supporting Information for details). However, complete decomposition occurred in distilling **3p**, **3t**, and **3w**.[24] Among these, pure **3p** and **3t** were partly obtained by column chromatography on alumina.

When a product is difficult to be isolated efficiently, its one-pot transformation via no purification is expected to be a smart choice. We therefore explored whether **3** being not isolated could be used directly as reagents for the Pd-catalyzed KMSCC reaction (Table 2). Thus, **3a** derived from **1a** and **2** was treated in one-pot with 4-bromobenzaldehyde (**5a**) under the reaction conditions given in Table 2,[2a] providing **6aa** in good yield of 74%.[25] Similarly, **3** based on a range of aryl and aliphatic alkynes **1** also coupled with **5a** to give **6ea**, **6ga**, **6ka**, **6pa**, **6ta**, and **6wa**, in which internal alkynes prepared from **3p**, **3t**, and **3w** with difficulty of being isolated are included. Moreover, BrPh (**5b**), 2-bromothiphene (**5c**), and alkenyl bromides **5d** and **5e** became the coupling partner of choice for this purpose (**6tb**, **6wc**, **6ed**, **6ae**). As a result, the one-pot KMSCC reaction proved to proceed without being negatively affected by the catalysts and solvent used for the 1st step on the Zn-catalyzed stannylation.

To further enhance the practicality of this reaction, we kept on executing the one-pot application, and next focused on alkynylstannylation of C≡C bonds for preparing more complex organostannanes. Firstly, the Pd–IP-catalyzed addition of **3a** to PhC≡CH was examined (Scheme 3). In this case, a procedure consisting of removing EtCN in vacuo after preparing **3a**, introducing THF instead, and conducting the next stage in THF is effective for obtaining **7a** as a single regioisomer.[26] Of note is that the yield and regioselectivity observed here are identical to those in the original report.[3a] Other than the palladium-based transformations, **3** added to the C≡C bond of benzyne derived from **8** under copper catalysis (Table 3).[3g] Here again, removing volatiles after the 1st step is

Table 2. Zn-catalyzed stannylation of terminal alkynes and Pd-catalyzed KMSCC reaction in one-pot.[a]

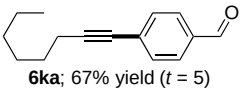




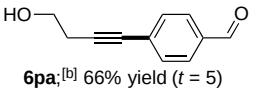
6aa (*X* = H); 74% yield (*t* = 5)

6ea (*X* = OMe); 78% yield (*t* = 5)

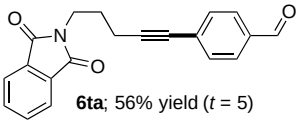
6ga (*X* = F); 82% yield (*t* = 5)



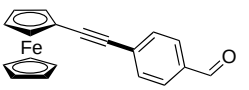
6ka; 67% yield (*t* = 5)



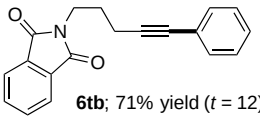
6pa;[b] 66% yield (*t* = 5)



6ta; 56% yield (*t* = 5)

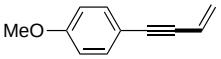


6wa; 60% yield (*t* = 5)

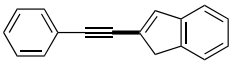


6tb; 71% yield (*t* = 12)

6wc; 71% yield (*t* = 12)

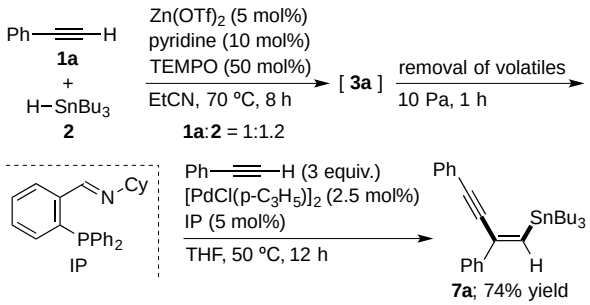


6ed;[c] 78% yield (*t* = 12)



6ae; 64% yield (*t* = 12)

[a] Reagents (unless otherwise noted): **1** (0.40 mmol), **2** (0.48 mmol), $Zn(OTf)_2$ (20 μmol), pyridine (40 μmol), TEMPO (0.20 mmol), EtCN (0.40 mL), and **5** (0.60 mmol), $Pd_2(dba)_3$ (6.0 μmol), P(^{t}Bu)$_3$ (13 μmol). Yields of isolated **6** based on **1** are shown here. [b] Performed with **2** (0.96 mmol) and TEMPO (0.40 mmol). [c] Performed with $Pd_2(dba)_3$ (12 μmol) and P(^{t}Bu)$_3$ (26 μmol).



7a; 74% yield

Scheme 3. Zn-catalyzed stannylation of PhC≡CH and Pd-catalyzed phenylethynylstannylation of PhC≡CH in one-pot. The yield of isolated **7a** based on **1a** is shown here. Cy = cyclohexyl.

effective,[27] giving (*o*-alkynylphenyl)stannanes **9a**, **9f**, **9t**, and **9w** in good to high yields. Interestingly, for example, **9a** was obtained in higher yield of 91%, compared to 70% yield of the original reaction starting with **3a**.[3g] To address the possible reason for the higher yield, how those used in the 1st step of the one-pot reaction affect the 2nd step was examined (Scheme 4). The Cu-catalyzed addition of **3a** to benzyne was thus carried out by adding $Zn(OTf)_2$, pyridine, TEMPO, or HSnBu$_3$ (**2**) to the reported conditions,[3g]

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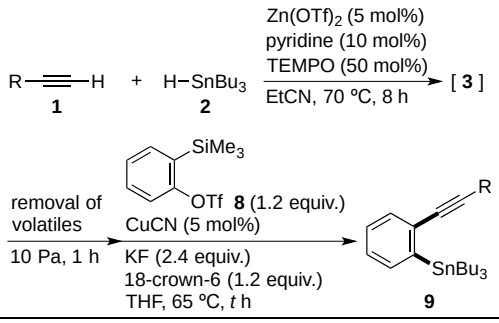
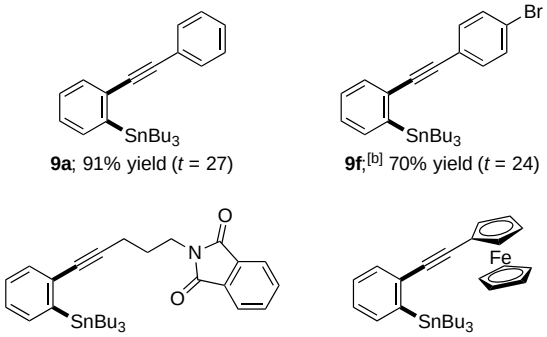
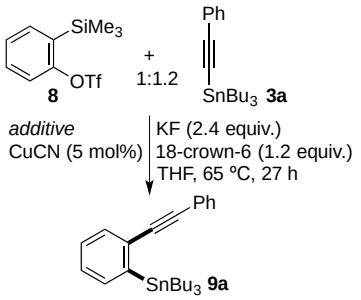
Table 3. Zn-catalyzed stannylation of terminal alkynes and Cu-catalyzed alkynylstannylation of benzyne in one-pot.[a]





[a] Reagents (unless otherwise noted): **1** (0.40 mmol), **2** (0.48 mmol), $Zn(OTf)_2$ (20 µmol), pyridine (40 µmol), TEMPO (0.20 mmol), EtCN (0.40 mL), and **8** (0.48 mmol), CuCN (20 µmol), KF (0.96 mmol), 18-crown-6 (0.48 mmol), THF (4.0 mL). Yields of isolated **9** based on **1** are shown here. [b] Performed with TEMPO (0.30 mmol).



additive (mol%)	Yield (%) of **9a**
none	70 (70)[a]
$Zn(OTf)_2$ (5)	88
pyridine (10)	37
TEMPO (50)	70
$HSnBu_3$ (20)	86

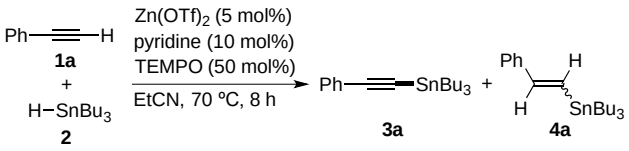
Scheme 4. Effect of additives in Cu-catalyzed phenylethynylstannylation of benzyne. Averages of yields determined by ^1H and ^{119}Sn NMR are shown here. [a] The yield reported in reference 3g is given in parentheses.

indicating that $Zn(OTf)_2$ and **2** favorably act to enhance the yield of **9a**. Accordingly, the one-pot recipe disclosed herein, which requires no pre-synthesis of **3** and gives **9** in higher yield, would be a better choice when **9** and also compounds derived from **9** are necessary.

Some experimental observations are available for mechanistic studies. We first examined the effect of each of $Zn(OTf)_2$, pyridine, and TEMPO, as shown in Table 4, where the result on the most suitable set is given in entry 1 for a reference. The independent use of $Zn(OTf)_2$ or pyridine resulted in the predominant hydrostannylation, but **3a** was selectively formed in 51% yield, even when using only 50 mol% of TEMPO (entries 2–4). However, using 100 mol% of TEMPO led to no quantitative yield of **3a** (entry 5). Combining TEMPO (50 mol%) with $Zn(OTf)_2$ (5 mol%) enhanced the yield of **3a** drastically (entry 6). This result may be acceptable enough, but the result of entry 1 reveals that the additional participation of pyridine is important for the complete selectivity and higher yield of **3a** (entries 1 and 6). None of the three led to exclusive hydrostannylation (entry 7). These results show that at least TEMPO and $Zn(OTf)_2$ is necessary for the selective and high-yield formation of **3a**.

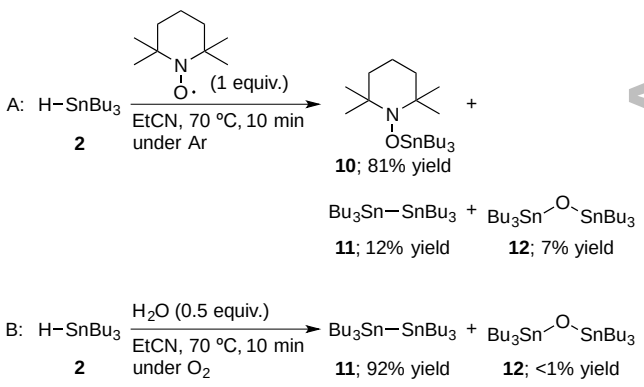
Based on the above, we further examined the role of TEMPO and $Zn(OTf)_2$. Thus, treating $HSnBu_3$ (**2**) and TEMPO in EtCN at 70 °C for only 10 min provided $TEMPOSnBu_3$ (**10**)[28] in 81% yield as a major product along with $Bu_3SnSnBu_3$ (**11**) in 12% yield (Scheme 5-A), as observed previously in benzene.[29] Besides **10** and **11**, $Bu_3SnOSnBu_3$ (**12**) was formed in a small amount. To ascertain the origin of the oxygen atom in **12**, as shown in Scheme 5-B, **2** was treated with H_2O but without TEMPO under O_2, thereby giving only **11**. This shows that the oxygen atom of **12** comes not from

Table 4. Effect of $Zn(OTf)_2$, pyridine and TEMPO in Zn-catalyzed stannylation of PhC≡CH with $HSnBu_3$.[a]



Entry	$Zn(OTf)_2$	pyridine	TEMPO	Yield (%)[b] **3a**	**4a**
1	○	○	○	94	<1
2	○	×	×	18	65
3	×	○	×	5	67
4	×	×	○	51	1
5	×	×	○[c]	19	1
6	○	×	○	90	1
7	×	×	×	<1	64

[a] Reagents (unless otherwise noted): **1a** (0.40 mmol), **2** (0.48 mmol), $Zn(OTf)_2$ (20 µmol), pyridine (40 µmol), TEMPO (0.20 mmol), EtCN (0.40 mL). [b] Averages of yields determined by ^1H and ^{119}Sn NMR are shown here. [c] TEMPO (100 mol%) was used.



Scheme 5. Reaction of $HSnBu_3$ with TEMPO (A) or H_2O (B). ^{119}Sn NMR yields based on **2** are shown here.

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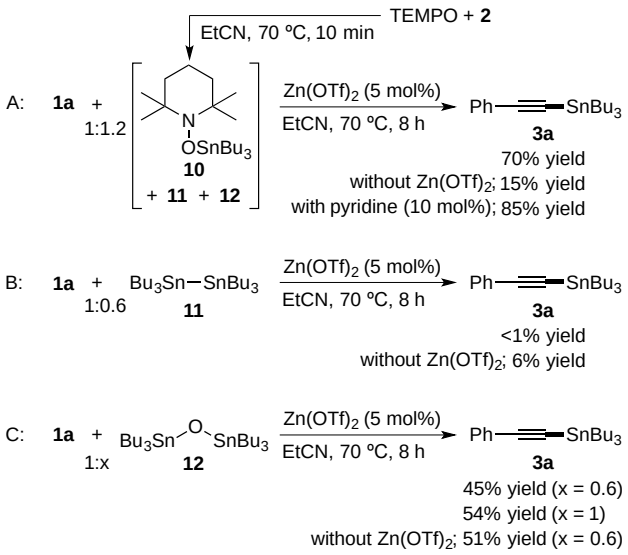
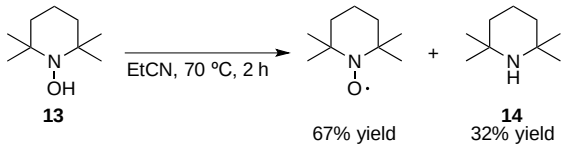


Scheme 6. Stoichiometric reaction of PhC≡CH (**1a**) with $TEMPOSnBu_3$ (A), $(Bu_3Sn)_2$ (B) or $(Bu_3Sn)_2O$ (C). Averages of yields determined by ^1H and ^{119}Sn NMR are shown here.

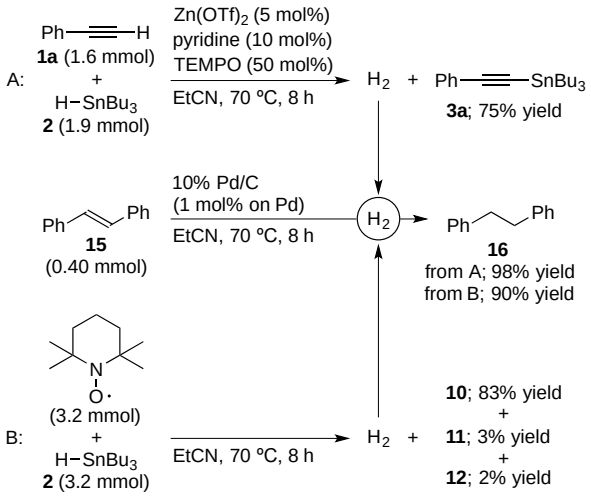
H_2O and O_2 but TEMPO, and thus that the formation of **12** would originate in breaking of the N–O bond, as reported before.[30] We next explored whether **10**, **11** or **12** has the ability to stannylate PhC≡CH (**1a**) (Scheme 6, in which **10** prepared in situ was used).[28] With **10** albeit including **11** and **12** as minors (see Scheme 5-A), **3a** was formed in good yield of 70%, but in low yield in the absence of $Zn(OTf)_2$ (Scheme 6-A). With both of $Zn(OTf)_2$ and pyridine, the yield of **3a** was improved, indicating that pyridine is an important supporter for the stannylation of alkynes, as shown in Table 4. In contrast, **11** was totally inactive, especially in the presence of $Zn(OTf)_2$ (Scheme 6-B). Although the stannylation proceeded moderately in the use of **12**,[31] $Zn(OTf)_2$ had no positive effect in this case (Scheme 6-C). Therefore, based on the results of Table 4 and Schemes 5 and 6, a key stannylating agent of the present reaction would be **10**, which is formed mainly from the reaction of TEMPO with **2**, and then stannylates **1a** more powerfully when $Zn(OTf)_2$ exists. The contribution of **12** is not negligible, but would be restrictive due to the small amount produced.

After the stannylation of **1a** by **10**, TEMPOH (**13**) is assumed to be formed along with **3a**. On the basis of this supposition, how **13** changes was next examined (Scheme 7). Upon simply heating **13** in EtCN for 2 h without the zinc and pyridine catalysts, a mixture of TEMPO and 2,2,6,6-tetramethylpiperidine (**14**) was quantitatively produced in a 2:1 ratio. Whereas **13** was partly reduced to **14**, the regeneration of TEMPO in the amount of two-thirds of **13** is likely to be sufficient for yielding **3a** in a high efficiency.[32]

Next, we confirmed whether hydrogen (H_2) gas is evolved via the progress of the stannylation reaction (Scheme 8). *trans*-Stilbene (**15**) was thus mixed with the palladium catalyst with the intention of capturing H_2 gas that is possibly formed from the Zn-catalyzed



Scheme 7. Reaction of TEMPOH. GC yields are shown here.

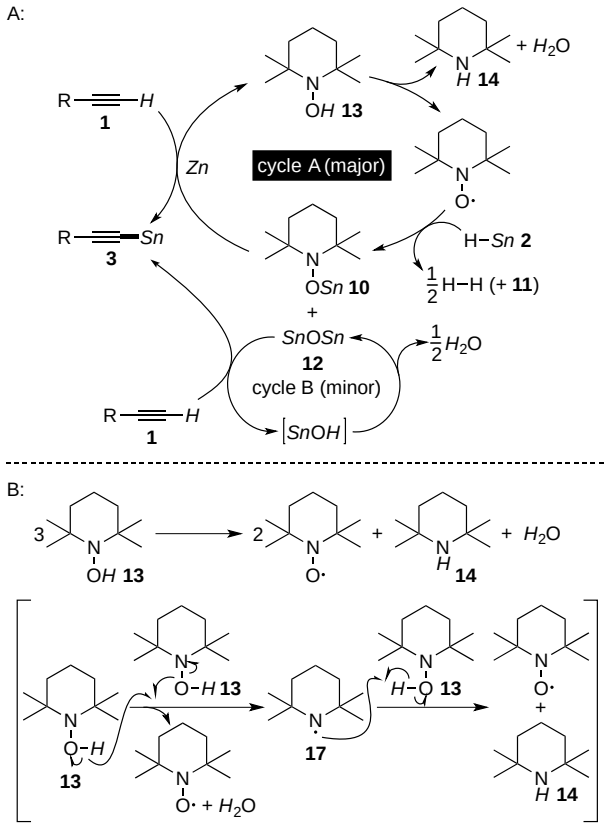


Scheme 8. Trapping experiments of hydrogen gas. Yields of isolated **3a** based on **1a** and of isolated **16** based on **15**, and also ^{119}Sn NMR yields of **10** and **12** based on TEMPO and of **11** based on **2** are shown here.

stannylation of **1a** with **2**, thereby giving 1,2-diphenylethane (**16**) in 98% yield (Scheme 8-A). However, just mixing TEMPO and **2** proved to release H_2 gas for the reduction of **15** (Scheme 8-B), thus suggesting that the source of H_2 gas is only **2**.

Taking all of the results from the mechanistic studies into consideration, a proposed mechanism is illustrated in Scheme 9-A. First up is the encounter of TEMPO and H–*Sn* (**2**) to give TEMPO*Sn* (**10**) and minor *Sn*O*Sn* (**12**) accompanied by the release of 1/2 H–H. Next, RC≡C*H* (**1**) undergoes stannylation by **10** with the aid of *Zn* to give desired RC≡C*Sn* (**3**) along with TEMPO*H* (**13**), which successively leads to regenerating TEMPO, along with the formation of **14** and H_2O. This would be a major pathway depicted as cycle A, and a detailed route from **13** to TEMPO is also proposed in Scheme 9-B, which starts with disproportionation of two molecules of **13** to give TEMPO, H_2O and piperidyl radical **17**. The subsequent abstraction of *H*• from another **13** by **17** provides TEMPO and **14**. Thus, it can be considered that, among the three molecules of **13**, two are oxidized to TEMPO and one is reduced to **14** via the redox disproportionation.[33] Considering in this way, the result of Scheme 7 in which TEMPO and **14** were formed in the 2:1 ratio would be rationally understood. Besides cycle A as a major route, cycle B, where **3** is formed from **1** and **12**, may participate as only a minor pathway.[34] At present, the exact role of pyridine is unclear, but could be to form an active species with *Zn*, as previously clarified in the zinc–pyridine–nitrile

system.[14f] When viewed as a whole, interestingly, a unique mechanism is operative here; both processes of the dehydrogenation ($-H_2$) and the oxidative dehydrogenation ($-H_2O$), which would be unlikely to coexist, are involved in a single reaction.



Scheme 9. Proposed reaction mechanisms. The *H* atom derived from **1** is shown in *italic*. *Zn* = $Zn(OTf)_2$. *Sn* = $SnBu_3$.

Conclusion

In closing, we have disclosed herein that the zinc–pyridine–nitrile system combined with TEMPO efficiently catalyzes the coupling of terminal alkynes with $HSnBu_3$. This is the first stannylation of the C–H bond under non-transition metal catalysis. This method is a reliable tool capable of offering a broad range of alkynyl–$SnBu_3$ with various functional groups, which are successfully available for further elaboration based on the KMSCC reaction as well as the alkynylstannylation of alkynes and arynes in one-pot. Mechanistic studies showed that $TEMPOSnBu_3$ formed in situ works as a key player with the cooperation of a zinc catalyst for the exclusive formation of the alkynyl–$SnBu_3$.

Experimental Section

Zinc-Catalyzed Stannylation of Terminal Alkynes with $HSnBu_3$: A General Procedure for Table 1

$Zn(OTf)_2$ (7.27 mg, 20.0 μmol) was placed in a 20 mL Schlenk tube, which was heated at 150 °C in vacuo for 1.5 h. The tube was cooled down to room temperature and filled with argon. EtCN (0.40 mL) was added to the tube (NOTE: EtCN over P_2O_5 in a distillation apparatus should not be used over 6 days to ensure reproducible results; the same applies hereinafter.), and the mixture was stirred at room temperature for 3 min. To this were added terminal alkyne **1** (0.400 mmol), tributyltin hydride (**2**) [(140 mg, 0.480 mmol) or (279 mg, 0.960 mmol)] (NOTE: the use of freshly distilled **2** is recommended to ensure reproducible results; the same applies hereinafter.), pyridine (3.16 mg, 40.0 μmol) and TEMPO [(31.3 mg, 0.200 mmol), (46.9 mg, 0.300 mmol) or (62.5 mg, 0.400 mmol)]. After stirring at 70 °C for 8 h, a saturated NH_4F aqueous solution (0.5 mL) was added to the mixture, and the aqueous phase was extracted with EtOAc (5 mL × 3). The combined organic layer was dried over anhydrous sodium sulfate. Filtration through a pad of Celite and evaporation of the solvent provided a crude mixture including desired product **3**, which was analyzed by ^1H and $^{119}Sn\{^1H\}$ NMR spectroscopy in $CDCl_3$. In the case of successively isolating product **3**, the following operations were performed. Thus, after evaporation of solvent $CDCl_3$ followed by diluting with EtOAc (15 mL), a 10 wt% NH_4F aqueous solution (10 mL) was added, and the resulting mixture was stirred at room temperature for 10 min. The aqueous phase was extracted with EtOAc (5 mL × 3), and the combined organic layer was dried over anhydrous sodium sulfate. Filtration through a pad of Celite and evaporation of the solvent followed by purification gave product **3**.

Zn-Catalyzed Stannylation of Terminal Alkynes and Pd-Catalyzed KMSCC Reaction in One-Pot: A General Procedure for Table 2

$Zn(OTf)_2$ (7.27 mg, 20.0 μmol) was placed in a 20 mL Schlenk tube, which was heated at 150 °C in vacuo for 1.5 h. The tube was cooled down to room temperature and filled with argon. EtCN (0.40 mL) was added to the tube, and the mixture was stirred at room temperature for 3 min. To this were added terminal alkyne **1** (0.400 mmol), tributyltin hydride (**2**) [(140 mg, 0.480 mmol) or (279 mg, 0.960 mmol)], pyridine (3.16 mg, 40.0 μmol) and TEMPO [(31.3 mg, 0.200 mmol) or (62.5 mg, 0.400 mmol)]. After stirring at 70 °C for 8 h and then cooling down to room temperature, aryl or alkenyl bromide **5** (0.60 mmol), $Pd_2(dba)_3$ [(5.49 mg, 6.00 μmol) or (11.0 mg, 12.0 μmol)], and a 10 wt% $P(^tBu)_3$ solution in hexanes (43.2 μL, 13.2 μmol) or (86.4 μL, 26.4 μmol) were added to the tube, and, under an argon atmosphere, the resulting mixture was stirred at room temperature for 5 or 12 h. A saturated NH_4F aqueous solution (0.5 mL) was added, and the aqueous phase was extracted with EtOAc (5 mL × 3). The combined organic layer was dried over anhydrous sodium sulfate. Filtration through a pad of Celite and evaporation of the solvent followed by column chromatography on silica gel gave product **6**.

Zn-Catalyzed Stannylation of PhC≡CH and Pd-Catalyzed Phenylethynylstannylation of PhC≡CH in One-Pot: A Procedure for Scheme 3

$Zn(OTf)_2$ (7.27 mg, 20.0 μmol) was placed in a 20 mL Schlenk tube, which was heated at 150 °C in vacuo for 1.5 h. The tube was cooled down to room temperature and filled with argon. EtCN (0.40 mL) was added to the tube, and the mixture was stirred at room temperature for 3 min. To this were added phenylacetylene (**1a**) (40.9 mg, 0.400 mmol), tributyltin hydride (**2**) (140 mg, 0.480 mmol), pyridine (3.16 mg, 40.0 μmol) and TEMPO (31.3 mg, 0.200 mmol). After stirring at 70 °C for 8 h and then cooling down to room temperature followed by concentration under reduced pressure of 10 Pa for 1 h, THF (3.6 mL), phenylacetylene (123 mg, 1.20 mmol), $[PdCl(\pi\text{-}C_3H_5)]_2$ (3.66 mg, 10.0 μmol) and IP (7.43 mg, 20.0 μmol) were added to the tube, and, under an argon atmosphere, the resulting mixture was stirred at 50 °C for 12 h. A saturated NH_4F aqueous solution (0.5 mL) was added, and the aqueous phase was extracted with EtOAc (5 mL × 3). The combined organic layer was dried over anhydrous sodium sulfate. Filtration through a pad of Celite and evaporation of the solvent gave a crude

product, which was successively purified by recycling GPC after filtration through a pad of silica gel (EtOAc) to give tributyl[(1*Z*)-2,4-diphenyl-1-buten-3-ynyl]stannane (**7a**) as a brown oil.

Zn-Catalyzed Stannylation of Terminal Alkynes and Cu-Catalyzed Alkynylstannylation of Benzyne in One-Pot: A General Procedure for Table 3

$Zn(OTf)_2$ (7.27 mg, 20.0 μmol) was placed in a 20 mL Schlenk tube, which was heated at 150 ºC in vacuo for 1.5 h. The tube was cooled down to room temperature and filled with argon. EtCN (0.40 mL) was added to the tube, and the mixture was stirred at room temperature for 3 min. To this were added terminal alkyne **1** (0.400 mmol), tributyltin hydride (**2**) (140 mg, 0.480 mmol), pyridine (3.16 mg, 40.0 μmol) and TEMPO [(31.3 mg, 0.200 mmol) or (46.9 mg, 0.300 mmol)], and the resulting mixture was then stirred at 70 ºC for 8 h. After cooling down to room temperature, the reaction mixture was concentrated under reduced pressure of 10 Pa for 1 h. In another 50 mL Schlenk tube were placed KF (55.8 mg, 0.960 mmol) and 18-crown-6 (127 mg, 0.480 mmol), which were evacuated at room temperature for 1 h and filled with argon. To the 50 mL Schlenk tube were added THF (2.0 mL) and CuCN (1.79 mg, 20.0 μmol) and was then transferred the solution in the 20 mL Schlenk tube through a cannula. THF (0.70 mL) was added to the 20 mL Schlenk tube, the inside of which was rinsed with the added THF, and the THF was transferred again through a cannula into the 50 mL Schlenk tube, and this operation was repeated a further twice with THF (0.70 mL + 0.60 mL). To the 50 mL Schlenk tube was added 2-(trimethylsilyl)phenyl trifluoromethanesulfonate (**8**) (143 mg, 0.480 mmol), and the resulting mixture was stirred at 65 ºC. After the time specified in Table 3, H_2O (0.5 mL) was added to the reaction mixture, and the aqueous phase was extracted with EtOAc (5 mL × 3). The combined organic layer was dried over anhydrous sodium sulfate. Filtration through a pad of Celite and evaporation of the solvent followed by column chromatography on silica gel gave product **9**.

Characterization data of and NMR spectra of products are collected in Supporting Information.

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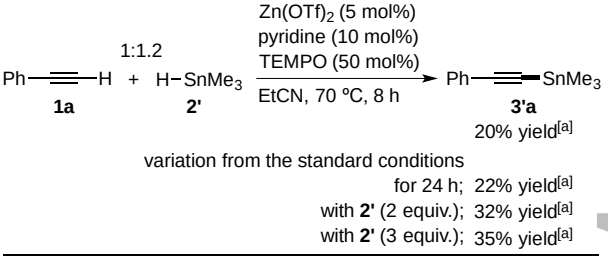
[21] The stannylation of **1a** with $HSnMe_3$ (**2'**) instead of **2** as a stannylating agent was also carried out under the standard and modified reaction conditions, as shown below. However, the use of **2'** resulted in lower yields of **3'a**, compared to that of **3a** when using **2**. Accordingly, further investigation on the scope of alkynes was conducted with **2**.



[a]Average yield determined by ^{1}H and ^{119}Sn NMR.

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[24] The decomposition of **3t** and **3w** is likely to be responsible for their high boiling points, and that of **3p** might be due to the proto-destannylation by the internal HO group.

[25] To identify whether the corresponding alkyne, PhC≡CH (**1a**), can couple with **5a** in the manner of the Sonogashira–Hagihara cross-coupling (SHCC) reaction under the reaction conditions, the same reaction except without using **2** was conducted but gave **6aa** in only 3% NMR yield, thus indicating that proto-destannylation of **3a** to give **1a** followed by the SHCC reaction with **5a** is not the major route for providing the 74% yield of **6aa**, in other words, the reaction conditions used for the 2nd step does not work for the SHCC reaction.

[26] One-pot reaction performed in EtCN without removing volatiles provided a 92:8 regioisomeric mixture of stannylenynes in 69% yield. The major isomer is **7a**, and the structure of the minor isomer is as follows:

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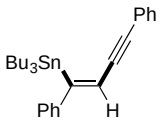

[27] For example, one-pot reaction of **1a** in EtCN conducted without removing volatiles gave **9a** in lower yield of 70%.

[28] Due to the instability under air, **10** could not be isolated but was detected by HRMS. See Supporting Information.

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[31] $(R_3Sn)_2O$ has been reported to work as a stannylating agent in benzene and THF. See reference 6.

[32] Assuming that all the processes where TEMPO is involved proceeds theoretically, at a first cycle, 33% of TEMPO is regenerated from 50% of TEMPO, which is the amount used first to alkyne **1**. Continuously, 22% of TEMPO from the resulting 33% of TEMPO is regenerated at a second cycle, and this sequence continues further. However, by summing up these, the total amount of TEMPO leading to TEMPO*Sn* **10** that can react with **1** is already over 100% (50% + 33% + 22% = 105%) at this stage.

[33] The same disproportionation of **13** has been proposed, see: A. Dijksman, A. Marino-González, A. M. i Payeras, I. W. C. E. Arends, R. A. Sheldon, *J. Am. Chem. Soc.* **2001**, *123*, 6826–6833.

[34] We could not find out a ^{119}Sn NMR spectrum of Bu_3SnOH (*Sn*OH) in $CDCl_3$ or C_6D_6 in the literature. On the other hand, since *Sn*OH in 1-methyl-2-pyrrolidone (NMP) has been reported to have a signal at ca. 48 ppm, a signal of *Sn*OH in $CDCl_3$ or C_6D_6 should be predicted to appear in a similar region. However, we have not observed any peak at the region in ^{119}Sn NMR spectra after stannylation reactions. Due to this, *Sn*OH is shown as a transient species with brackets in Scheme 9-A. For the ^{119}Sn NMR spectrum of Bu_3SnOH in NMP, see: V. Farina, S. Kapadia, B. Krishnan, C. Wang, L. S. Liebeskind, *J. Org. Chem*. **1994**, *59*, 5905–5911.

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FULL PAPER

A Drastic Effect of TEMPO in Zinc-Catalyzed Stannylation of Terminal Alkynes with Hydrostannanes via Dehydrogenation and Oxidative Dehydrogenation

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