## C-C Coupling Reactions

## Nickel-Catalyzed Tandem Carbostannylation of Alkynes and 1,2-Dienes with Alkynylstannanes\*\*

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Carbometalation of carbon-carbon unsaturated bonds affords versatile synthetic reagents that have a newly formed carbon-carbon bond and a carbon-metal bond, which can be used for further construction of carbon frameworks.<sup>[1]</sup> In particular, a series of transition-metal-catalyzed carbostannylations<sup>[2]</sup> of alkynes,<sup>[3]</sup> 1,3-dienes<sup>[4]</sup> and 1,2dienes<sup>[5]</sup> provides us with various substituted organostannanes, which are converted into a variety of conjugated and nonconjugated olefinic compounds through carbon-carbon bond forming reactions such as the Kosugi-Migita-Stille coupling.<sup>[6]</sup> The high chemoselectivity and mild reactivity of organostannanes make the sequence of carbostannylation and subsequent carbon-carbon bond-forming reactions an attractive synthetic strategy. Herein, we report an example of a tandem carbostannylation reaction,<sup>[7]</sup> namely, sequential insertion of two different carbon-carbon unsaturated bonds into a tin–alkynyl carbon bond.<sup>[8]</sup>

Treatment of trimethyl(phenylethynyl)tin (1a, 0.10 mmol) with 1-octyne (2a, 0.60 mmol) and 1,2-heptadiene (3, 0.30 mmol) in the presence of  $[Ni(cod)_2]$  (5.0 µmol) and [2-(dimethylamino)phenyl]diphenylphosphane (pn, 5.0 µmol; dibutyl ether, 50 °C, 24 h) gave rise to tandem alkynylstannylation to give a 98:2 mixture<sup>[9]</sup> of (3Z,6Z)-3-hexyl-1-phenyl-6-(trimethylstannyl)undeca-3,6-dien-1-yne (4a) and (3Z,6E)-

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 Table 1:
 Nickel-catalyzed tandem alkynylstannylation of alkynes and 1,2-heptadiene.<sup>[a]</sup>



Entry	R <sup>1</sup>	R <sup>2</sup>	Cond. <sup>[b]</sup>	<i>t</i> [h]	Yield [%] <sup>[c]</sup>	4:5 <sup>[c]</sup>	Product(s)
1	Ph ( <b>1 a</b> )	Hex ( <b>2 a</b> )	А	24	56	98:2	4a, 5 a
	. ,		В	24	73	4:96	4a, 5 a
			С	24	55	1:>99	5 a
2 <sup>[d]</sup>	Ph ( <b>1</b> ′a)	Hex ( <b>2 a</b> )	А	24	33	82:18	4′a, 5′a
			В	24	49	1:>99	5′a
			С	49	12	1:>99	5′a
3	Ph ( <b>1 a</b> )	Me <sub>3</sub> SiCH <sub>2</sub> (2b)	А	24	49	96:4	4b, 5 b
		( )	В	24	59	12:88	4b, 5 b
			С	24	35	14:86	4b, 5 b
4	Ph ( <b>1 a</b> )	Me <sub>3</sub> Si ( <b>2c</b> )	А	6	5	>99:1	4c
		- ( )	В	8	31	10:90	4c, 5 c
			С	6	31	7:93	4c, 5 c
5	$CH_2 = CMe (1b)$	Hex ( <b>2 a</b> )	А	4.5	44	>99:1	4d
	2 ( )		В	6	67	6:94	4d, 5 d
			С	24	31	9:91	4d, 5 d
6	Et₃Si ( <b>1 c</b> )	Hex ( <b>2 a</b> )	А	10	61	51:49	4e, 5e
	/	. ,	В	9	60	5:95	4e, 5e
			С	8	57	8:92	4e, 5e

[a] The reaction was carried out in solvent (0.15 mL) with an alkynylstannane (0.10 mmol), an alkyne (0.60 mmol) and 1,2-heptadiene (0.30 mmol) in the presence of  $[Ni(cod)_2]$  (5.0 µmol) and a ligand. [b] Ligand and solvent for Conditions A: pn (5.0 µmol), dibutyl ether; B: ttpp (10 µmol), toluene; C: dpp (5.0 µmol), THF. [c] Determined by <sup>119</sup>Sn NMR spectroscopy with Me<sub>4</sub>Sn (Bu<sub>4</sub>Sn for entry 2) as an internal standard. [d] Tributyl(phenylethynyl)tin was used instead of the trimethylstannyl analogue.

isomer **5a** in 56% yield [Eq. (1) and entry 1 of Table 1].<sup>[10]</sup> Screening of effective ligands led us to find that tris[p-(trifluoromethyl)phenyl]phosphane (ttpp) and 2-(diphenylphosphanyl)pyridine (dpp) gave the products in comparable yields<sup>[11]</sup> (entry 1 of Table 1) but in preference for **5a** over **4a** for conditions B and C (see Figure 1). Worthy of note is that **4a** or **5a** is generated in each case with selectivities higher than 96% out of 48 possible isomers.



 $\it Figure 1.$  Ligands and solvents used in the tandem alkynylstannylation for conditions A, B, and C.

The tandem alkynylstannylation conditions A (pn in dibutyl ether), B (ttpp in toluene) or C (dpp in THF) were applied to various alkynylstannanes, alkynes and 1,2-heptadiene (entries 2–6 of Table 1). Tributylstannyl(phenyl)acetylene ( $\mathbf{1'a}$ ) also participated in the reaction (entry 2) but less efficiently. Similarly, stannyldienynes **4** and **5** that have a trimethylsilylmethyl or trimethylsilyl substituent were prepared (entries 3 and 4). Enynyl- and silylethynylstannanes also gave the corresponding trienynes and dienynes, respectively (entries 5 and 6). In addition to terminal alkynes and a monosubstituted allene, an internal alkyne and a 1,1-disubstituted allene reacted, albeit with much lower yields (Scheme 1).

Tandem alkynylstannylation of bis(trimethylstannyl)acetylene 9 with 2a and 3 gave 1:2:2 adducts 10 predominantly, whereas bis(tributylstannyl) analogue 9' gave a mixture of 1:1:1 adducts 11' [Eq. (2)]. The stereochemical preferences change depending on whether conditions A or B are used, as before. Thus, the size of trialkylstannyl groups effectively controls the ratio of 10:11 or 10':11'.

Some pieces of evidence are available to contribute towards a discussion of the mechanism of the tandem reaction. An oxidative adduct of tributyl(phenylethynyl)tin ( $\mathbf{1'a}$ ) to a Ni<sup>0</sup>-pn complex was observed by <sup>31</sup>P NMR and



**Scheme 1.** Tandem alkynylstannylation by using an internal alkyne or a 1,1-disubstituted allene. Reagents and conditions are the same as those in Table 1.

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## Communications



<sup>119</sup>Sn NMR spectroscopies (Scheme 2), $^{[12,13]}$  while the reaction of  $[Ni(cod)_2]$ -pn with trimethylstannyl analogue **1a** gave a complex mixture. On treatment of **1'a** with  $[Ni(cod)_2]$ 



**Scheme 2.** Oxidative addition of an alkynylstannane to a nickel(0)-pn complex and the subsequent reactions traced by <sup>31</sup>P NMR and <sup>119</sup>Sn NMR spectroscopies: [a] Percentage of integral with respect to all of the observed peaks; [b] Yield based on 1'a (determined by <sup>119</sup>Sn NMR spectroscopy with Bu<sub>4</sub>Sn as an internal standard); [c]  $J_{P^{-119}Sn}$  and  $J_{P^{-117}Sn}$  were not resolved.

(1.0 equiv) and pn (1.0 equiv) in *N*-methylpyrrolidone (NMP)<sup>[14]</sup> in an NMR tube, two sets (**12**–pn A and **12**–pn B) of distinct signals were observed both in <sup>31</sup>P NMR and <sup>119</sup>Sn NMR spectra. Although the observed  $J_{P-Sn}$  values in both sets A and B indicate that a Sn–Ni  $\sigma$  bond is formed *cis* to the P atom,<sup>[15]</sup> thus suggesting structure **12**–pn shown in Scheme 2, we do not understand why two sets of peaks were observed. Both of these sets did not change on addition of alkyne **2a** (1.0 equiv) but did so smoothly with 1,2-diene **3** (1.2 equiv) to give **13**,<sup>[16]</sup> which lacks Sn–P coupling, thus showing that the insertion of **3** took place at the Ni–Sn bond of **12**–pn.<sup>[17]</sup> All attempts to obtain **4'a** or any other carbostannylation products by the reaction of **13** with **2a** were unsuccessful.

A survey of side products in the tandem alkynylstannylation of **1a**, **2a**, and **3** also provided information on the reaction order. Formation of any alkyne-alkynylstannylation product was not observed to any extent under conditions A, B, or C,<sup>[18]</sup> whereas a small amount of an allene-alkynylstannylation product was isolated under conditions A and B.<sup>[19]</sup> The results clearly show that 1,2-diene **3** rather than alkyne **2a** reacts with **12**–pn.

With the above data in hand, cycles 1 and 2 (see Scheme 3) may rationally explain the formation of tandem alkynylstan-



**Scheme 3.** Plausible catalytic cycles that start with oxidative addition of an alkynylstannane to a nickel (0) complex.

nylation products 4a and 5a from the reaction of 1a with 2a and 3. The catalytic cycles start with oxidative addition of 1a to a nickel(0) complex. When oxidative adduct 12 undergoes insertion of 3 in a manner similar to acylstannane-nickel(0) oxidative adducts,<sup>[20]</sup> 3 should insert into the Ni-Sn bond of 12 in a direction such to avoid steric repulsion of the Bu substituent to give an (E)- $\sigma$ -allylnickel complex,<sup>[21]</sup> which is prone to isomerize into the more stable *anti*- $\pi$ -allyl complex 14. Alkyne 2a should then insert into the bond between the nickel atom and the nonsubstituted allyl carbon atom of 14 or the corresponding syn-isomer 15.<sup>[22,23]</sup> The stereoselectivity of the tandem alkynylstannylation products should be determined by the relative rate of insertion of 2a into the Ni-C bond of 14 and anti-syn isomerization from 14 to 15, depending on ligand pn, ttpp or dpp. Reductive elimination from 16 or 17 should finally afford 4a or 5a, respectively.<sup>[24]</sup>

In conclusion, we have disclosed the first example of transition-metal-catalyzed tandem carbostannylation of two different carbon–carbon unsaturated bonds. Nickel catalysts assemble alkynylstannanes, alkynes and 1,2-dienes into alkenylstannanes having a dienyne structure that is otherwise hard to access by a direct route. Studies on the details of the mechanism as well as application of the reaction to other substrates are in progress.

## **Experimental Section**

Tandem alkynylstannylation of alkynes and 1,2-dienes, general procedure: 1,2-Diene (0.30 mmol) and an alkyne (0.60 mmol) were added to a solution that contained an alkynylstannane (0.10 mmol),  $[Ni(cod)_2]$  (1.4 mg, 5.1 µmol) and a ligand (pn: 1.5 mg, 4.9 µmol; ttpp: 4.7 mg, 10 µmol; dpp: 1.3 mg, 4.9 µmol) in a solvent (dibutyl ether, toluene, or THF: 0.15 mL), and the resulting mixture was stirred at 50 °C. After the time specified (see Table 1 and Scheme 1 for specific details), the mixture was diluted with diethyl ether and filtered through a pad of florisil. The crude product was analyzed by <sup>119</sup>Sn NMR spectroscopy with Me<sub>4</sub>Sn (Bu<sub>4</sub>Sn for the reaction of tributyl(phenylethynyl)tin) as an internal standard.

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- [10] Unless otherwise noted, the yields and the ratio of isomers were determined by <sup>119</sup>Sn NMR spectroscopy with Me<sub>4</sub>Sn or Bu<sub>4</sub>Sn as an internal standard.
- [11] The isolated yield of 4a and 5a after purification with reversed phase chromatography (octadecylsilyl, ODS) followed by gelpermeation chromatography (GPC) under conditions A or B (Figure 1) was 50% (88:12) or 63% (2:98), respectively,

obtained from independent experiments from those shown in Table 1, entry 1.

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- [14] Oxidative adduct 12-pn was observed also in dibutyl ether, THF, [D<sub>6</sub>]benzene or DMF but in a purity less than 50%. NMP as a solvent for the Ni-pn-catalyzed reaction of 1a with 2a and 3 was found to be as efficient as dibutyl ether in the yield and stereoselectivity.
- [15] The J<sub>P-Sn(cis)</sub> of oxidative adduct of 1'a to a palladium-iminophosphane or dppp complex is reported to be 21 or 29 Hz, respectively, whereas the J<sub>P-Sn(rans)</sub> of the dppp complex is 1479/1411 Hz. See, E. Shirakawa, H. Yoshida, T. Hiyama, *Tetrahedron Lett.* **1997**, *38*, 5177-5180. The J<sub>P-19Sn(cis)</sub> and J<sub>P-19Sn(rans)</sub> of a similar complex, [(dppe)Pd(SnMe<sub>2</sub>Cl)(C≡CMe)], prepared by successive transmetalation of the corresponding dichloro complex, are reported to be 183 and 2392 Hz. See, C. Stader, B. Wrackmeyer, J. Organomet. Chem. **1985**, *295*, C11-C15.
- [16] Complex **12-pn** reacted with **3** also in the presence of **2a** (1.0 equiv) to give **13**.
- [17] We could not obtain further information on the structure of complex 13: its short lifetime and insufficient purity in addition to low availability of deuterated NMP do not allow us to gain meaningful <sup>13</sup>C and <sup>1</sup>H NMR spectra.
- [18] The reaction of **1a** with **2a** in the absence of **3** under conditions A or B gave (*Z*)-2-hexyl-4-phenyl-1-trimethylstannylbut-1-en-3yne in 13% or 6% yield, respectively. For the nickel-catalyzed alkynylstannylation of alkynes, see reference [3b].
- [19] (Z)-4-Trimethylstannyl-1-phenylnon-4-en-1-yne or 3-butyl-5phenyl-2-trimethylstannylpent-1-en-4-yne was generated in 6% yield under conditions A or B, respectively. For the nickelcatalyzed alkynylstannylation of 1,2-dienes, see reference [5b].
- [20] In the nickel-catalyzed acylstannylation of 1,2-dienes, oxidative adducts of acylstannanes to nickel(0) complexes are considered to accept insertion of 1,2-dienes at the Ni–Sn bonds in the direction that affords σ-allylnickel complexes. See reference [5a].
- [21] Intermediary σ-allylnickel complexes, which should be involved in cycle 1 and 2, are omitted from Scheme 3 for clarity.
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- [23] When allylnickel complexes fail to accept insertion of 2a, alkynylstannylation products of 3 should be generated through reductive elimination.
- [24] Oxidative cyclization of 2a and 3 with a nickel(0) complex followed by the reaction with 1a may be an alternative mechanism, but no evidence is currently available. See reference [7].

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