Homogeneous Catalysis

Distannylation of Strained Carbon–Carbon Triple Bonds Catalyzed by a Palladium Complex**

Hiroto Yoshida, Kenji Tanino, Joji Ohshita, and Atsutaka Kunai**

Transformations of arynes catalyzed by a transition-metal complex, although less common than stoichiometric reactions,[1] have recently received considerable attention as a novel route for the synthesis of substituted arenes that are not accessible by conventional methods. Irrespective of the catalyst and reactant used, efforts have thus far been devoted mainly to developing cyclization reactions of arynes. The pioneering work on these transformations—palladium-catalyzed trimerization of arynes[2] and cocyclization of arynes

---

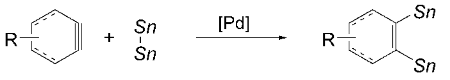
[*] Dr. H. Yoshida, K. Tanino, Prof. J. Ohshita, Prof. A. Kunai
Department of Applied Chemistry
Graduate School of Engineering
Hiroshima University
Higashi-Hiroshima 739-8527 (Japan)
Fax: (+81) 82-424-5494
E-mail: yhiroto@hiroshima-u.ac.jp
akunai@hiroshima-u.ac.jp

[**] We thank Central Glass Co Ltd. for a generous gift of trifluoromethanesulfonic anhydride.

Supporting information for this article is available on the WWW under http://www.angewandte.org or from the author.

DOI: 10.1002/ange.200460189

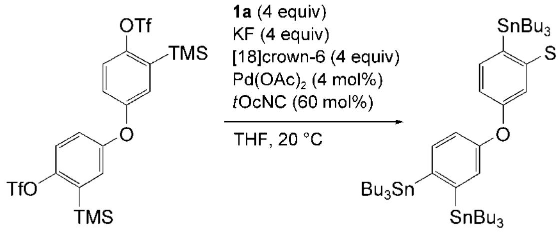
with alkynes[3]—was reported by Peña et al. Catalytic reactions of arynes with alkynes and/or allyl chlorides in the presence of a palladium complex have also been reported by Yamamoto and co-workers,[4] while Murai and co-workers have developed cobalt-, rhodium-, and palladium-catalyzed carbonylative cycloadditions of arynes.[5] Catalytic addition reactions of a σ bond[6] to arynes have been limited to carbostannylation[7a] and disilylation,[7b] as reported previously. Herein we report that a tin–tin bond of a distannane readily adds to strained carbon–carbon unsaturated compounds, such as arynes or cyclohexynes, in the presence of a palladium complex [Eq. (1)]. This transition-metal-catalyzed element–element σ-bond addition reaction to cyclohexynes has no precedents, to the best of our knowledge.



(1)

We first examined the reaction of hexabutyldistannane (**1a**) and benzyne, prepared in situ from 2-(trimethylsilyl)phenyl triflate (**2a**),[8] and a fluoride ion (KF/[18]crown-6) in the presence of a palladium/1,1,3,3-tetramethylbutyl isocyanide (*tert*-octyl isocyanide, *t*OcNC) complex,[9] and found that the tin–tin bond of **1a** smoothly adds to benzyne to afford 1,2-bis(tributylstannyl)benzene (**3aa**) in 73% yield (entry 1, Table 1).[10] The choice of catalyst and source of the fluoride ion are crucial: the reaction did not proceed in the presence of either [Pd(dba)$_2$] (dba = *trans*,*trans*-dibenzylideneacetone) or [Pd(PPh$_3$)$_4$], and the desired product was also not formed when CsF in MeCN[11] was used as the source of the fluoride ion, even in the presence of the same palladium–isocyanide complex. The distannylation of various arynes was then investigated under the optimized reaction conditions. As in the case of benzyne itself, the 4-substituted benzynes formed in situ from precursors **2b**–**2d** react efficiently with **1a** to provide the corresponding distannylation products **3ab**–**3ad**, respectively, in moderate to high yields (entries 2–4), whereas the reaction of 4-fluorobenzyne (formed from **2e**) gave only a low yield of the desired product (entry 5). The distannylation reaction was also applied to 4,5-disubstituted benzynes (formed from **2f** or **2g**) or sterically more congested arynes (formed from **2h**–**2j**) to afford good to high yields of products **3af**–**3aj**, respectively (entries 6–10). In addition to **1a**, hexamethyldistannane (**1b**) could also be used as the tin-containing starting material, and in this case the less-reactive 1,2-naphthalyne (from **2k**), 3-phenylbenzyne (from **2l**), or 9,10-phenanthryne (from **2m**) were found to insert into the tin–tin bond (entries 11–14, respectively);[12] in most cases a compound resulting from cyclotrimerization of the aryne (triphenylene) was formed as a by-product. The reaction with **1b** also produced a trace amount of 2,2′-distannylbiaryl as well; for example, triphenylene and 2,2′-bis(trimethylstannyl)biphenyl were obtained in 9% and 3% yields in the reaction summarized in entry 11.

The reaction of an aryne containing two triple bonds is noteworthy: treatment of the bisaryne precursor **2n** with **1a** gave bis[3,4-bis(tributylstannyl)phenyl] ether **3an** in which four carbon–tin bonds are formed in one step [Eq. (2); Tf = trifluoromethanesulfonyl, TMS = trimethylsilyl].



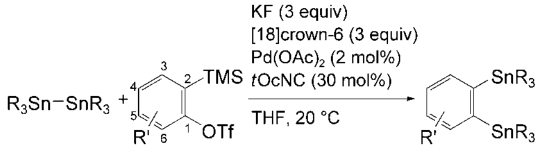
(2)

2n **3an**: 30% (24 h)

The distannylation reaction was also found to be suitable for cyclohexynes (Scheme 1). When in situ generated cyclohexyne (formed from **2o**) was treated with **1a** under the above-mentioned reaction conditions the insertion product 1,2-bis(tributylstannyl)cyclohexene (**3ao**) was obtained in 70% yield. Similarly, the reaction of substituted cyclohexynes (formed from **2p** or **2q**) with **1b** also took place successfully to provide the distannylation products (**3bp** or **3bq**) in 60 or 90% yield, respectively.

Since an aryl (or alkenyl) triflate readily undergoes a cross-coupling reaction with a distannane in the presence of a palladium catalyst,[13] the distannylation might proceed by a pathway that does not

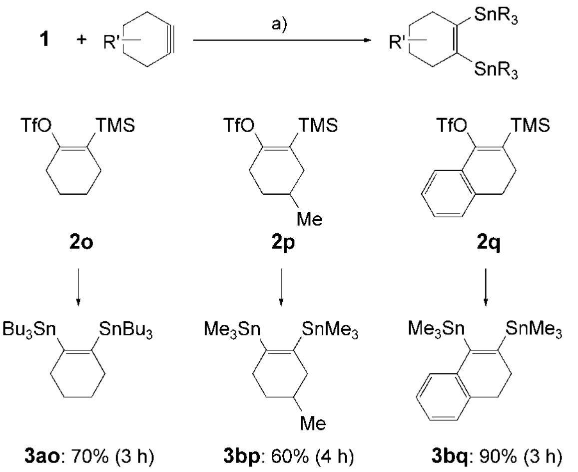
Table 1: Distannylation of arynes.



1 **2** **3**

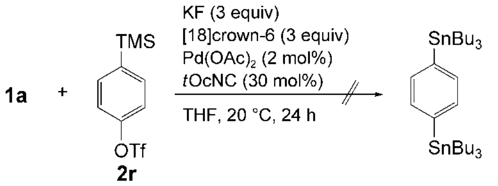
Entry	Distannane	R′ in **2**	Precursor	*t* [h]	Yield [%][a]	Product
1	**1a** (R = Bu)	H	**2a**	3	73	**3aa**
2		4-Me	**2b**	3	71	**3ab**
3		4-MeO	**2c**	7	55	**3ac**
4		4-Ph	**2d**	4	40	**3ad**
5		4-F	**2e**	6.5	26	**3ae**
6		4,5-Me$_2$	**2f**	3	73	**3af**
7		4,5- -(CH$_2$)$_3$-	**2g**	9	64	**3ag**
8		6-Me	**2h**	3.5	55	**3ah**
9		3-MeO	**2i**	6	59	**3ai**
10		3,6-(MeO)$_2$	**2j**	5	63	**3aj**
11	**1b** (R = Me)	H	**2a**	4	56	**3ba**
12		3,4- -(CH)$_4$-	**2k**	4.5	61	**3bk**
13		6-Ph	**2l**	5.5	39	**3bl**
14		dibenzo[c,e][b]	**2m**	5	27	**3bm**

[a] Yield of isolated product based on distannane. [b] 9,10-Phenanthryne.



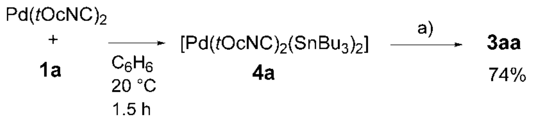
Scheme 1. Distannylation of cyclohexynes: a) KF (3 equiv), [18]crown-6 (3 equiv), Pd(OAc)$_2$ (2 mol%), *t*OcNC (30 mol%), THF, 20°C.

involve an aryne (cyclohexyne) intermediate: cross-coupling of **2** at a C–OTf moiety with **1** followed by fluoride-ion-induced silicon–tin exchange between the resulting 2-(trialkylstannyl)arylsilane (2-(trialkylstannyl)cyclohexenylsilane) and R$_3$SnOTf.[14] However, this pathway can be ruled out since the reaction of 4-(trimethylsilyl)phenyl triflate (**2r**) with **1a** did not give the respective distannylation product, thus confirming the intermediacy of an aryne (cyclohexyne) in the distannylation process [Eq. (3)].

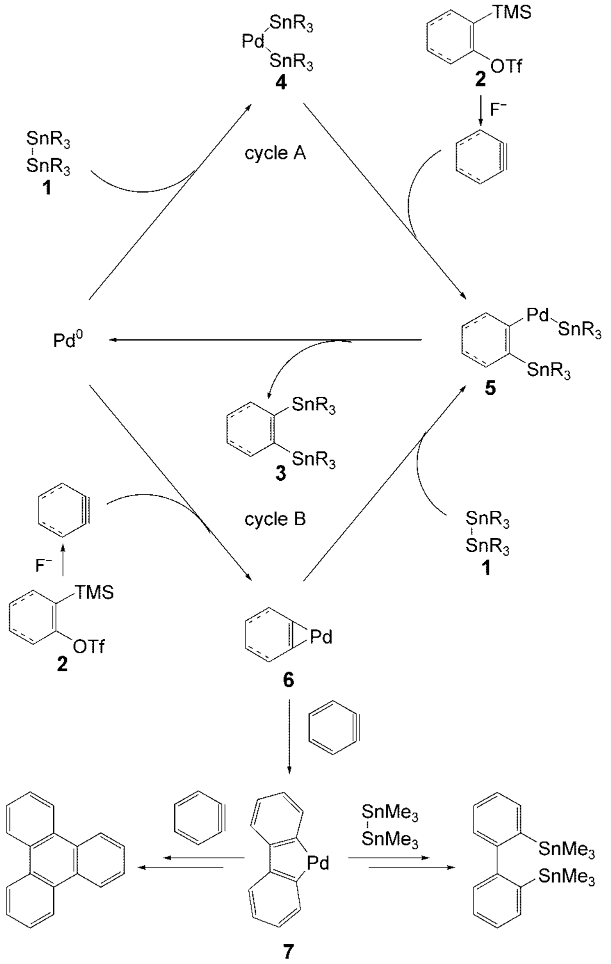


(3)

We assumed that this reaction is initiated by oxidative addition of an Sn–Sn bond of a distannane to a Pd^0 complex[15] and thus we examined the stoichiometric reaction shown in Scheme 2. Thus, treatment of the Pd^0–isocyanide complex[16]



Scheme 2. Elucidation of the mechanism by stoichiometric reactions: a) **2a** (1.5 equiv), KF (3 equiv), [18]crown-6 (3 equiv), THF, 20°C, 1 h.



Scheme 3. Catalytic cycles for the distannylation.

with an equimolar amount of **1a** led to the quantitative formation of the oxidative-addition product **4a**,[17,18] which exhibits high reactivity for the insertion of benzyne to afford **3aa** in 74% yield. These results prompted us to propose cycle A depicted in Scheme 3. First, complex **4** is produced by oxidative addition of **1** to the Pd^0 complex. Subsequent insertion of the triple bond of the aryne or cyclohexyne into an Sn–Pd bond of **4** to form palladium complex **5**, followed by reductive elimination, affords the product and regenerates the catalyst. However, formation of a triphenylene and distannylbiaryl as by-products may suggest that another catalytic cycle is also operative. Thus, the Pd^0 complex initially undergoes oxidative cyclization with the aryne to generate palladacycle **6**,[19] which yields the product after reaction with **1** (cycle B).[20,21] The by-products could also arise from **6**: the interaction of **6** with a second aryne instead of **1** gives a five-membered palladacycle **7**, which reacts further with a third aryne[22] or **1**[23] to afford a triphenylene or distannylbiaryl, respectively.

In conclusion, distannylation of arynes or cyclohexynes has been accomplished in the presence of a catalytic amount of a palladium–*tert*-octyl isocyanide complex, and diverse 1,2-distannylarenes or 1,2-distannylcyclohexenes, which could have high synthetic utility as bis(anion) equivalents, have been readily synthesized. Moreover, the catalytic pathway, which includes oxidative addition of a distannane to a palladium(0) complex, has been confirmed by the stoichiometric reaction. Further studies on synthetic applications to other strained cycloalkynes and σ bonds are in progress.

Experimental Section

3aa: Compounds **1a** (0.13 g, 0.22 mmol) and **2a** (0.098 g, 0.33 mmol) were added to a solution (1.0 mL) of 1,1,3,3-tetramethylbutyl isocyanide (9.2 mg, 0.066 mmol), Pd(OAc)$_2$ (1.0 mg, 4.4 μmol), KF (0.038 g, 0.66 mmol) and [18]crown-6 (0.17 g, 0.66 mmol) in THF, and the resulting mixture was stirred at 20 °C for 3 h. The mixture was then diluted with ethyl acetate, filtered through celite, and concentrated. Column chromatography on alumina (hexane as eluent, activity IV) followed by gel-permeation chromatography (benzene as eluent) gave **3aa** as a colorless oil (0.11 g, 73% yield); ^{1}H NMR (400 MHz, CDCl$_3$): $\delta = 0.88$ (t, $J = 7.1$ Hz, 18H), 1.01–1.07 (m, 12H), 1.27–1.53 (m, 24H), 7.19–7.22 (m, 2H), 7.42–7.55 ppm (m, 2H); ^{13}C NMR (99.5 MHz, CDCl$_3$): $\delta = 10.9$, 13.6, 27.5, 29.2, 127.1, 137.5, 151.9 ppm; ^{119}Sn NMR (147.5 MHz, CDCl$_3$): $\delta = -43.2$ ppm. Elemental analysis calcd for C$_{30}$H$_{58}$Sn$_2$: C 54.91, H 8.91; found: C 55.18, H 8.97.

Received: April 1, 2004

Keywords: arynes · cycloalkynes · homogeneous catalysis · palladium · tin

---

[1] Reviews: a) S. L. Buchwald, R. B. Nielsen, *Chem. Rev.* **1988**, *88*, 1047; b) S. L. Buchwald, R. D. Broene, in *Comprehensive Organometallic Chemistry II*, *Vol. 12* (Eds.: E. W. Able, F. G. A. Stone, G. Wilkinson), Pergamon, Oxford, **1995**, pp. 771–784; c) M. A. Bennett, H. P. Schwemlein, *Angew. Chem.* **1989**, *101*, 1349; *Angew. Chem. Int. Ed. Engl.* **1989**, *28*, 1296; d) M. A. Bennett, E. Wenger, *Chem. Ber./Recl.* **1997**, *130*, 1029.

[2] a) D. Peña, S. Escudero, D. Pérez, E. Guitián, L. Castedo, *Angew. Chem.* **1998**, *110*, 2804; *Angew. Chem. Int. Ed.* **1998**, *37*, 2659; b) D. Peña, D. Pérez, E. Guitián, L. Castedo, *Org. Lett.* **1999**, *1*, 1555; c) D. Peña, A. Cobas, D. Pérez, E. Guitián, L. Castedo, *Org. Lett.* **2000**, *2*, 1629.

[3] a) D. Peña, D. Pérez, E. Guitián, L. Castedo, *J. Am. Chem. Soc.* **1999**, *121*, 5827; b) D. Peña, D. Pérez, E. Guitián, L. Castedo, *Synlett* **2000**, 1061; c) D. Peña, D. Pérez, E. Guitián, L. Castedo, *J. Org. Chem.* **2000**, *65*, 6944.

[4] a) K. V. Radhakrishnan, E. Yoshikawa, Y. Yamamoto, *Tetrahedron Lett.* **1999**, *40*, 7533; b) E. Yoshikawa, K. V. Radhakrishnan, Y. Yamamoto, *Tetrahedron Lett.* **2000**, *41*, 729; c) E. Yoshikawa, Y. Yamamoto, *Angew. Chem.* **2000**, *112*, 185; *Angew. Chem. Int. Ed.* **2000**, *39*, 173; d) E. Yoshikawa, K. V. Radhakrishnan, Y. Yamamoto, *J. Am. Chem. Soc.* **2000**, *122*, 7280.

[5] N. Chatani, A. Kamitani, M. Oshita, Y. Fukumoto, S. Murai, *J. Am. Chem. Soc.* **2001**, *123*, 12686.

[6] Reviews on the addition of σ bonds to unsaturated organic compounds: a) I. Beletskaya, C. Moberg, *Chem. Rev.* **1999**, *99*, 3435; b) M. Suginome, Y. Ito, *Chem. Rev.* **2000**, *100*, 3221.

[7] a) H. Yoshida, Y. Honda, E. Shirakawa, T. Hiyama, *Chem. Commun.* **2001**, 1880; b) H. Yoshida, J. Ikadai, M. Shudo, J. Ohshita, A. Kunai, *J. Am. Chem. Soc.* **2003**, *125*, 6638.

[8] a) Y. Himeshima, T. Sonoda, H. Kobayashi, *Chem. Lett.* **1983**, 1211; b) D. Peña, A. Cobas, D. Pérez, E. Guitián, *Synthesis* **2002**, 1454.

[9] A palladium–isocyanide complex has been shown by Ito and coworkers to be an efficient catalyst for disilylation, silylstannylation, or silylboration of unsaturated organic compounds such as alkynes and alkenes, see Ref. [6b].

[10] For the palladium-catalyzed distannylation of alkynes, see a) T. N. Mitchel, A. Amamria, H. Killing, D. Rutschow, *J. Organomet. Chem.* **1983**, *241*, C45; b) E. Piers, R. T. Skerlj, *J. Chem. Soc. Chem. Commun.* **1986**, 626; c) J. Mancuso, M. Lautens, *Org. Lett.* **2003**, *5*, 1653.

[11] The combination of CsF and MeCN has been employed frequently in the catalytic transformations of arynes, see Ref. [3–5] and [7a].

[12] No trace of the distannylation products of these arynes was found in the reaction with **1a**.

[13] a) S. A. Hitchcock, D. R. Mayhugh, G. S. Gregory, *Tetrahedron Lett.* **1995**, *36*, 9085; b) G. Stork, R. C. A. Isaacs, *J. Am. Chem. Soc.* **1990**, *112*, 7399.

[14] B. P. Warner, S. L. Buchwald, *J. Org. Chem.* **1994**, *59*, 5822.

[15] Oxidative addition of a distannane to a palladium(0) complex has been proposed to be an initiation step in the distannylation of alkynes, see Ref. [6a].

[16] a) S. Otsuka, A. Nakamura, Y. Tatsuno, *J. Am. Chem. Soc.* **1969**, *91*, 6994; b) M. Suginome, H. Oike, S.-S. Park, Y. Ito, *Bull. Chem. Soc. Jpn.* **1996**, *69*, 289.

[17] The configuration of **4a** (*cis* or *trans*) could not be elucidated.

[18] Oxidative addition of a distannane to a palladium(0)–phosphane complex: Y. Tsuji, K. Nishiyama, S. Hori, M. Ebihara, T. Kawamura, *Organometallics* **1998**, *17*, 507.

[19] M. Retbøll, A. J. Edwards, A. D. Rae, A. C. Willis, M. A. Bennett, E. Wenger, *J. Am. Chem. Soc.* **2002**, *124*, 8348; see also Ref. [1c] and [1d].

[20] The palladium-catalyzed carbostannylation of arynes has also been reported to proceed via palladacycle **6**: T. Matsubara, *Organometallics* **2003**, *22*, 4297; see also Ref. [7a].

[21] We could not substantiate cycle B by a stoichiometric reaction because an attempt to prepare palladacycle **6** by the reaction of [Pd(*t*OcNC)$_2$] with **2a** and KF/[18]crown-6 was unsuccessful.

[22] The five-membered palladacycle **7** has been proposed to be a key intermediate in the palladium-catalyzed trimerization of arynes, see Ref. [2a].

[23] The reaction of a five-membered palladacycle, derived from a Pd^0 complex and 2 mol of an alkyne, with an organostannane has been demonstrated to be a key step in the palladium-catalyzed dimerization-carbostannylation of alkynes: a) E. Shirakawa, H. Yoshida, Y. Nakao, T. Hiyama, *J. Am. Chem. Soc.* **1999**, *121*, 4290; b) H. Yoshida, E. Shirakawa, Y. Nakao, Y. Honda, T. Hiyama, *Bull. Chem. Soc. Jpn.* **2001**, *74*, 637.