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Efficient Synthesis of Diborylalkenes from Alkenes and Diboron by a New PSiP-Pincer Palladium-Catalyzed Dehydrogenative Borylation

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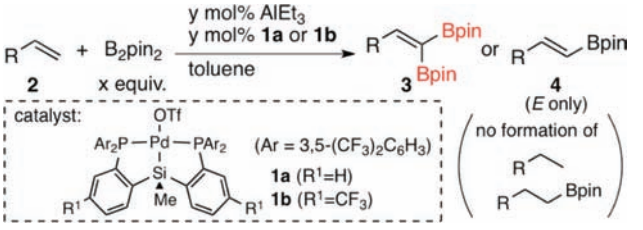
Supporting Information

ABSTRACT: The efficient synthesis of various diborylalkenes such as 1,1-, *trans*-1,2-, and cyclic 1,2-diborylalkenes from alkenes and diboron was achieved for the first time. Selective preparation of di- and monoborylalkenes was also realized by the appropriate choice of reaction conditions. The reaction was found to proceed via a new mechanism of dehydrogenative borylation through a monoborylpalladium complex bearing an anionic PSiP-pincer ligand as a key intermediate, which realized the efficient borylation without sacrificial hydroboration or hydrogenation of the alkene.

Diborylalkenes have attracted much attention as versatile building blocks in organic synthesis because these compounds enable further multiple carbon−carbon bond formations via Pd-catalyzed cross-coupling reactions, leading to facile stereoselective construction of π-conjugated materials and biologically active compounds such as tamoxifen and polyene natural products.[1,2] Several methods for the preparation of these classes of compounds have been reported, but most of them necessitate multistep procedures along with the use of specific stoichiometric reagents.[3−6] Probably the most general method is the Pt-catalyzed diboration of alkynes, but only *cis*-1,2-diborylalkenes are available by this method.[7] Thus, it is highly desirable to develop a concise method for the preparation of 1,1- and *trans*-1,2-diborylalkenes starting from simple alkenes and diboron to expand the utility of diborylalkenes.[8] Herein we report a highly efficient protocol for the synthesis of such molecules through PSiP-pincer palladium-catalyzed double dehydrogenative borylation of alkenes with diboron, by which a variety of diborylalkenes can be prepared *without sacrificial hydroboration or hydrogenation of the alkene*. The reaction involves a monoborylpalladium(II) complex as the key catalytic species.

It was found that treatment of a 1:2 mixture of styrene and B_2pin_2 with a 2.0 mol % loading of a PSiP-pincer palladium catalyst with 3,5-bis(trifluoromethyl)phenyl groups on phosphorus (**1a**) and $AlEt_3$ in toluene at room temperature gave the 1,1-diborylation product, β,β-diborylstyrene **3a**, in 90% yield (Table 1, entry 1).[9−11] The same reaction with 1.0 equiv of B_2pin_2 selectively gave the monoborylation product, (*E*)-styrylboronic ester **4a**, in 92% yield stereoselectively (entry 2). It should be noted that analysis of the crude mixture by GC−MS showed the formation of HBpin, but neither hydroboration nor hydrogenation products were observed at all. This selective synthesis of mono- or 1,1-diborylalkenes depending on the amount of the diboron was also applicable to other electronically activated alkenes. Vinylferrocene (**2b**) and *N*-vinylphthalimide (**2c**) gave the corresponding 1,1-diborylalkenes **3b** and **3c** in high yield with the use of 2 or 3 equiv of B_2pin_2 with a 5 mol % loading of the more active electron-withdrawing PSiP-pincer catalyst **1b** at 60 °C (entries 3 and 5), whereas the reaction using 1.0 equiv of B_2pin_2 with catalyst **1a** at the same temperature afforded monoborylation products **4b** and **4c** in high yield with excellent *E* selectivity (entries 4 and 6).

Table 1. Selective Synthesis of 1,1-Diboryl- and Monoborylalkenes



Entry	Alkene	Loading of B_2pin_2	Catalyst	Product[a]	3:4
1	R = Ph **2a**	2.0 equiv.	2 mol% **1a**, rt, 24 h	**3a** 90%	≥50:1
2		1.0 equiv.	2 mol% **1a**, rt, 24 h	**4a** 92%	1:≥50
3	R = Fc **2b**	2.0 equiv.	5 mol% **1b**, 60 °C, 6 h	**3b** 92%	≥50:1
4		1.0 equiv.	5 mol% **1a**, 60 °C, 6 h	**4b** 93%	1:≥50
5	R = phthalimide **2c**	3.0 equiv.	5 mol% **1b**, 60 °C, 6 h	**3c** 86%[b]	29:1
6		1.0 equiv.	5 mol% **1a**, 60 °C, 6 h	**4c** 91%	1:≥50

[a] Isolated yields are shown. [b] The monoborylation product **4c** was obtained in 3% yield.

Another novel aspect of this reaction was disclosed when nonelectronically activated, sterically less demanding terminal alkenes were employed as substrates. Thus, the reaction of allyl(triphenyl)silane (**2d**) under diborylation conditions using 2 mol % catalyst **1b** exhibited another mode of diborylation, trans-1,2-diborylation, to give (*Z*)-1,2-diborylalkene **5d** selectively in 80% yield (Table 2, entry 1). The structure and *Z* geometry of **5d** were confirmed by X-ray analysis [see the Supporting Information (SI)]. It should be noted that this product is a highly useful module for multiple carbon−carbon bond formations, and there has been no general method for the synthesis of such trisubstituted trans-diborylated alkenes. Furthermore, the monoborylation protocol using 1.0 equiv of

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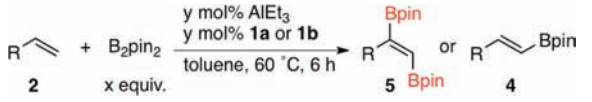
Table 2. Selective Synthesis of *trans*-1,2-Diboryl- and Monoborylalkenes

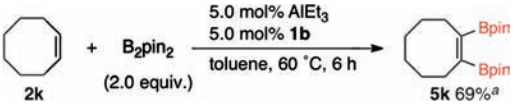


Entry	Alkene	Loading of B_2pin_2	Catalyst	Product[a]	*E*:*Z*[b]	5:4
1	R = $-CH_2SiPh_3$ **2d**	2.0 equiv.	2 mol% **1b**	**5d** 80%	*Z* only	≥50:1
2		1.0 equiv.	1 mol% **1a**	**4d** 84%[c]	75:25	1:≥50
3	R = $-CH_2SiMe_3$ **2e**	2.0 equiv.	1 mol% **1b**	**5e** 82%	4:96	≥50:1
4		1.0 equiv.	1 mol% **1a**	**4e** 58%[d]	87:13	1:4.5
5	R = $-CH_2$-*c*-C_5H_9 **2f**	3.0 equiv.	10 mol% **1a**	**5f** 85%	22:78	≥50:1
6		1.0 equiv.	10 mol% **1a**	**4f** 43%[e]	93:7	1:3.3
7	R = OTBS, Ph **2g**	2.0 equiv.	10 mol% **1a**	**5g** 68%	11:89	≥50:1
8		1.0 equiv.	10 mol% **1a**	**4g** 62%[f]	88:12	1:4.1
9	R = $-CH_2CH_2Cl$ **2h**	2.0 equiv.	10 mol% **1a**	**5h** 48%[g]	9:91	6.9:1
10		1.0 equiv.	10 mol% **1a**	**4h** 53%[h]	92:8	1:18
11	R = **2i**	2.0 equiv.	10 mol% **1a**	**5i** 59%	*Z* only	≥50:1
12		1.0 equiv.	10 mol% **1a**	**4i** 87%[i]	86:14	1:≥50
13[j]	R = $-(CH_2)_5CH_3$ **2j**	3.0 equiv.	10 mol% **1a**	**5j** 63%	19:81	≥50:1
14[j]		–[k]	10 mol% **1a**	**4j** 85%	93:7	1:≥50

[a] Isolated yields are shown, unless otherwise noted. [b] Determined by ^1H NMR analysis. [c] (*Z*)-**4d** was obtained as a mixture with a small amount of 1-propenyl(triphenyl)silane and some isomers. [d] Obtained as a mixture with **5e** (13%). [e] **5f** (13%) was also obtained. [f] **5g** (15%) was also observed (NMR yield). [g] Obtained as a mixture with **4h** (7%) and dechlorinated product (1%). [h] **5h** (3%) was also obtained. [i] NMR yield. [j] In THF. [k] The reaction was carried out in the presence of 3.0 equiv of alkene with respect to B_2pin_2, and the yield of **4j** was based on B_2pin_2.

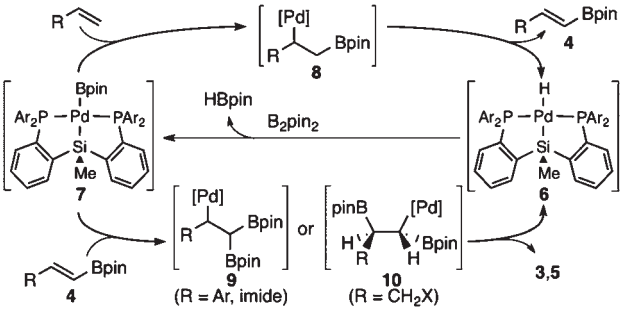
B_2pin_2 was also successful in this case, affording monoborylated allylsilane **4d** in good yield (entry 2). Various other terminal alkenes also turned out to undergo the trans-1,2-diborylation. Allyl(trimethyl)silane (**2e**) and allylcyclopentane (**2f**) afforded (*Z*)-1,2-diborylalkenes **5e** and **5f**, respectively, in good yield with good stereoselectivity when >2 equiv of B_2pin_2 was used (entries 3 and 5), whereas the use of 1.0 equiv of B_2pin_2 gave the corresponding monoborylation products **4e** and **4f** in moderate yield (entries 4 and 6). This reaction demonstrated good compatibility with functional groups. Thus, silyl ether, chloro, and acid anhydride moieties were not affected under the reaction conditions, and functionalized (*Z*)-1,2-diborylalkenes **5g**−**i** and alkenylboronic esters **4g**−**i** were obtained in moderate to good yields under the appropriate conditions (entries 7−12). The 1,2-diborylation of simple alkenes such as 1-octene also proceeded without problem when the reaction was carried out in THF (entry 13), although the monoborylation required the use of an excess amount of the alkene to obtain alkenylboronic ester **4j** in high yield (entry 14).[12] Furthermore, this 1,2-diborylation protocol was applicable to cyclooctene, giving *cis*-1,2-diborylcyclooctene **5k**, which is not available by the Pt-catalyzed diboration protocol, in good yield (Scheme 1).[13] These results

Scheme 1. 1,2-Diborylation of Cyclooctene[a]



[a] The monoborylated alkene (30%) was also obtained.

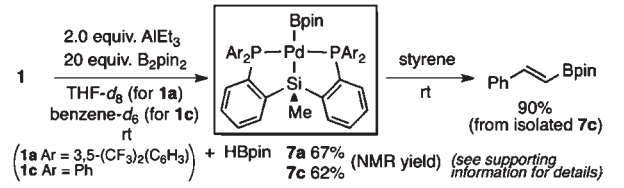
Scheme 2. Proposed Mechanism



are the first example of an efficient synthesis of *trans*-1,2-diboryl- and cyclic 1,2-diborylalkenes from alkenes, and a selective route to synthetically useful diboryl- and monoborylalkenes has also been developed. Therefore, this new borylation reaction should find abundant use in organic synthesis.

The reaction is thought to proceed through double dehydrogenative borylation of the alkene in which the alkene reacts with a monoborylpalladium(II) complex bearing an anionic PSiP-pincer ligand as the key catalytic species, resulting in complete suppression of sacrificial hydroboration or hydrogenation of the alkene (Scheme 2). First, the triflate complex **1** undergoes transmetalation with $AlEt_3$ followed by β-hydride elimination to generate monohydridopalladium complex **6**,[14] which reacts with B_2pin_2 to give HBpin and monoborylpalladium complex **7** bearing the PSiP-pincer ligand. Borylpalladium **7** undergoes alkene insertion and β-hydride elimination to give the monoborylation product **4** with regeneration of palladium hydride **6**, which immediately reacts with B_2pin_2 to regenerate the key catalytic species, borylpalladium **7**. A second borylation of **4** in the presence of excess B_2pin_2 gives the diborylation product **3** or **5** with high regioselectivity depending on the kind of substituent on the alkene. The predominant trans selectivity in 1,2-diborylation is reasonably explained by considering a syn-insertion/syn-elimination mechanism via alkylpalladium(II) intermediate **10**.[15] Most of the previously reported dehydrogenative borylations of alkenes with diboron or borane have been limited to monoborylation, and sacrificial hydroboration and/or hydrogenation of the alkene are inevitable problems caused by coordinatively unsaturated hydrido(boryl)- or dihydridometal species (**A** or **B**, respectively) generated by the reaction of the metal catalyst with borane or dihydrogen produced during the reaction.[16,17] Therefore, an excess amount of alkene is usually required.[18,19] Szábo recently reported dehydrogenative borylation of alkenes under oxidative conditions involving a monoborylpalladium(IV) complex as a proposed intermediate, but the reaction requires a stoichiometric oxidant such as $PhI(TFA)_2$ for the Pd(II)/Pd(IV) catalytic cycle and excess alkene is still required.[20] On the

Scheme 3. Synthesis of a Monoborylpalladium Complex Bearing an Anionic PSiP-Pincer Ligand and Its Reaction with Styrene



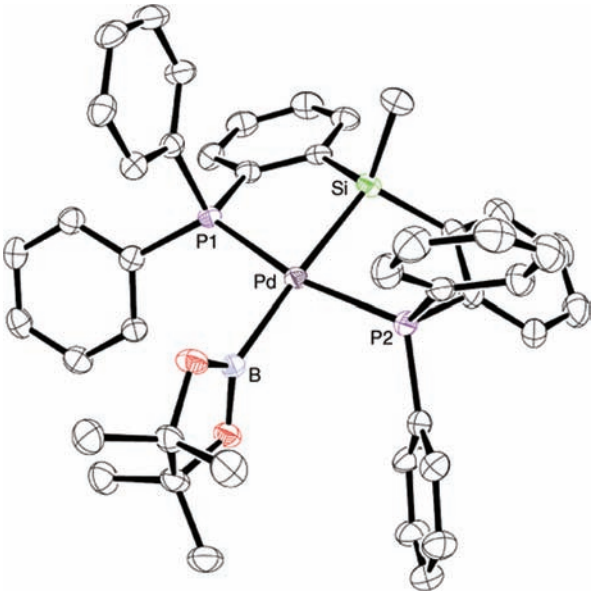


Figure 1. ORTEP diagram of monoborylpalladium complex **7c** bearing a PSiP-pincer ligand (Ar = Ph) at the 50% probability level (H atoms have been omitted for clarity). Selected bond lengths (Å) and angles (deg): Pd—B, 2.112(4); Pd—Si, 2.3795(11); Pd—P1, 2.2532(10); Pd—P2, 2.2489(11); P1—Pd—P2, 163.17(4).

contrary, our catalytic cycle consists of monohydrido- and monoborylpalladium(II) complexes (**6** and **7**) and does not generate such metal species (**A** and **B**) because of the characteristics of the anionic tridentate pincer-type ligand, resulting in an efficient reaction without sacrificial hydroboration or hydrogenation of the alkene under oxidant-free conditions.

In support of this mechanism, it was found that treatment of a mixture of palladium triflate **1a** and 20 equiv of B_2pin_2 in THF-d_8 with $AlEt_3$ at room temperature afforded borylpalladium complex **7a** along with generation of HBpin (Scheme 3). The structure of the borylpalladium complex was confirmed by X-ray analysis for Ar = Ph (**7c**) (Figure 1), and the Pd—B distance was found to be 2.11 Å, which is longer than those in previously reported borylpalladium complexes [1.97—2.08 Å for Pd—BX_2 (X = O, N)][21] because of the strong trans influence of Si,[22] realizing high catalytic activity of this reaction. Moreover, **7c** was confirmed to undergo borylation of an alkene smoothly with regeneration of the palladium hydride (see the SI). More detailed mechanistic studies of the formation of borylpalladium **7** and the origin of the regioselectivity in the second borylation step are in progress.

In conclusion, we have developed an efficient method for the synthesis of various types of diborylalkenes from alkenes via palladium-catalyzed double dehydrogenative borylation. The unprecedented mechanism involving a monoborylpalladium complex bearing the PSiP-pincer ligand, leading to selective reactions without sacrificial hydroboration nor hydrogenation, has also been disclosed. This protocol provides the new possibility of utilizing alkenylboronic esters as a module for multiple carbon—carbon bond formation in synthetic organic chemistry.

■ ASSOCIATED CONTENT

Supporting Information. Preparative methods, spectral and analytical data for compounds **1**—**5** and **7**, and crystallographic data (CIF). This material is available free of charge via the Internet at http://pubs.acs.org.

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(10) The catalytic activity depended on the electron density of the Ar_2P moiety and increased as Ar = *p*-$MeOC_6H_4$ < Ph < *p*-$CF_3C_6H_4$ < 3,5-$(CF_3)_2C_6H_3$.

(11) The reaction in the absence of $AlEt_3$ did not proceed at all.

(12) The monoborylation of **2j** under the standard conditions (alkene:B_2pin_2 = 1:1, THF) gave **4j** in low yield (~20%), probably as a result of a competing isomerization reaction of the double bond.

(13) At present, the reaction of cyclic alkenes does not proceed with sufficient generality. For example, although the monoborylation of cycloheptene proceeded in high yield, diboration conditions afforded several products probably formed by migration of the double bond. Cyclohexene did not react under the present conditions.

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(15) The proposed mechanism cannot explain the reaction of cyclooctene to give (*Z*)-1,2-diboryloctene. Formation of allylboronic ester and its isomerization may be operative in this case, as proposed for the Rh-catalyzed reaction. For examples, see: Kondoh, A.; Jamison, T. F. *Chem. Commun.* **2010**, *46*, 907.

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