# Nickel-Catalyzed Addition of Alkynylboranes to Alkynes

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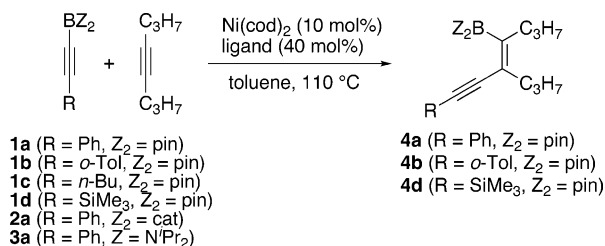Received July 12, 2006; E-mail: suginome@sbchem.kyoto-u.ac.jp

Organoboranes play indispensable roles in organic synthesis, for instance as versatile synthetic intermediates for complex organic molecules. The recent development of boron-based organic synthesis has largely relied on the exploration of new transition-metal catalyzed reactions of organoboron compounds, such as Suzuki–Miyaura coupling,[1] Rh-catalyzed conjugative additions,[2] and Ru-catalyzed CH/organoborane cross-coupling systems.[3] On the other hand, an increasing effort has been devoted to the efficient synthesis of organoboron compounds. It should be noted here that transition metal catalyses also play major roles in the synthesis of organoboranes. In comparison with the conventional synthesis, for example, uncatalyzed hydroboration, the catalytic reactions often provide highly efficient and selective access to functionalized organoboron compounds.[4] Recent developments in this field involve catalytic diborations,[5] stannaborations,[6] silaborations,[7] and CH-borylation reactions.[8]

Our recent interest has focused on transition metal-catalyzed carboboration reactions in which C−C and B−C bonds are formed within a single catalytic cycle.[9,10] We successfully demonstrated both "direct"[9] and "transmetalative"[10] carboboration strategies, which involve the activation of a B−C bond and a B−Cl bond, respectively. The "direct" carboboration seems to be more efficient than the other from the viewpoint of atom economy, although it often encounters difficulties in effective activation of the B−C bond (eq 1). A similar strategy has already been established in the synthesis of organostannanes via "direct" transition metal-catalyzed carbostannation reactions.[11] Our success in the first "direct" carboboration was largely due to the reactivity of boron cyanides, whose B−CN bond is rather easily activated by transition metals. Indeed, no other catalytic carboboration of alkynes that involves oxidative addition of the B−C bond has been reported. Herein, we report new direct carboboration, in which the B−C bond of an alkynylborane adds across the carbon−carbon triple bond of an alkyne. The intermolecular alkynylboration proceeds in the presence of phosphine-nickel catalysts, giving 1-borylbut-1-en-3-yne derivatives in good yields.[12] The scope and synthetic utility of the reaction are discussed.

$$(1)$$
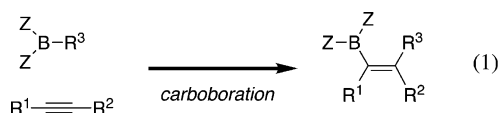
Reactions of alkynylboranes **1**−**3** with 4-octyne were carried out in the presence of transition metal catalysts (Table 1). Our trials using palladium catalysts having phosphine ligands such as PMe₃, PCy₃, PPh₃, and DPPE at 140 °C in xylene all failed. Switching the catalysts to nickel−phosphine systems turned out to be promising (Table 1). Although no reaction took place with a ligand-free or PPh₃-coordinated nickel catalyst (entries 1 and 2), a reaction using PCyPh₂−Ni(cod)₂ as catalyst resulted in the formation of alkynylboration product **4a** albeit in low yield (entry 3). A much improved yield was attained with PCy₂Ph as ligand, which afforded

Table 1. Reactions of Alkynylboranes with 4-octyne in the Presence of Nickel Complexes[a]

1a (R = Ph, Z₂ = pin)
1b (R = o-Tol, Z₂ = pin)
1c (R = n-Bu, Z₂ = pin)
1d (R = SiMe₃, Z₂ = pin)
2a (R = Ph, Z₂ = cat)
3a (R = Ph, Z = N^{i}Pr₂)

4a (R = Ph, Z₂ = pin)
4b (R = o-Tol, Z₂ = pin)
4d (R = SiMe₃, Z₂ = pin)

entry	BZ₂	R	ligand	time h	yield %[b]	cis/ trans[c]
1	B(pin)	Ph	none	3	0	
2	B(pin)	Ph	PPh₃	3	0	
3	B(pin)	Ph	PCyPh₂	10	20	83:17
4	B(pin)	Ph	PCy₂Ph	2	69	85:15
5	B(pin)	Ph	PCy₃	0.5	65	90:10
6	B(pin)	Ph	PMe₃	3	0	
7	B(cat)	Ph	PCy₂Ph	2	0	
8	B(N^{i}Pr₂)₂	Ph	PCy₂Ph	3	0	
9	B(pin)	o-Tol	PCy₂Ph	2	83	90:10
10	B(pin)	n-Bu	PCy₂Ph	2	trace	
11	B(pin)	SiMe₃	PCy₂Ph	0.5	89	91:9

[a] Alkynylborane (**1**, **2**, or **3**) (0.20 mmol) and 4-octyne (1.0 mmol) in toluene (0.5 mL) were heated at 110 °C in the presence of Ni(cod)₂ (0.020 mmol) with the phosphine ligands (0.080 mmol) unless otherwise noted. [b] Yields were determined by ¹H NMR using dibenzyl ether as an internal standard. [c] Determined by GC.

the alkynylboration product in 69% yield with a cis/trans ratio of 85:15 (entry 4). It should be remarked that our previous report on the alkynylboration using chloroborane as the boron source resulted in *trans*-alkynylboration,[10] whereas the present reaction system achieved *cis*-alkynylboration. We also found that the PCy₃−nickel catalyst promoted the reaction even at 70 °C, whereas the PCy₂Ph system hardly promoted the reaction at the same temperature. Reactions using PCy₃ at 110 °C had to be stopped after a shorter reaction time than did reactions with PCy₂Ph (entry 5). In sharp contrast to these ligands, a PMe₃−Ni(cod)₂ catalyst showed no catalytic activity at all (entry 6).

Another aspect of the reaction is the dependence of the reactivity on the substituents on boron. In contrast to the successful formation of the alkynylboration products with the pinacolborane derivative, the corresponding catechol derivative gave a complex mixture (entry 7) and the diisopropylamino derivative resulted in no reaction (entry 8). The alkynyl substituent of the alkynylborane was then varied. *o*-Tolyl-substituted alkynylborane added effectively to 4-octyne in good yield (entry 9). In comparison with the phenyl-substituted alkynylborane (entry 4), the more sterically demanding *o*-tolyl derivative gave a higher yield. In contrast, the reaction of alkyl-substituted **1c** proceeded only sluggishly, giving a complex mixture containing a trace amount of an alkynylboration product, which could be detected by MS spectroscopy (entry 10). It should be

Table 2. Ni-Catalyzed Alkynylboration of Alkynes with **1d**[a]

entry	R¹	R²	product	% yield[b]	regio-selectivity[c]	cis/trans[d]
1[e]	n-Pr	n-Pr	4d	92 (99)		92:8
2	CH₂Ph	CH₂Ph	5	67 (76)		96:4
3	Ph	Me	6	57 (62)	81:19	90:10
4	Ph	Et	7	65 (79)	92:8	87:13
5	Ph	n-Bu	8	68 (80)	93:7	89:11
6	p-Anis	n-Bu	9	71 (99)	93:7	73:27
7	1-Nap	Me	10	51 (79)	88:12	99:1
8	p-EtO₂CC₆H₄	n-Bu	11	51 (79)	92:8	93:7
9	Ph	(CH₂)₂CH=CH₂	12	60 (72)	94:6	89:11

[a] To a mixture of **1d** (0.50 mmol), Ni(cod)₂ (0.025 mmol), and PCy₃ (0.10 mmol) in toluene (0.2 mL) was added alkyne (0.55 mmol) over 1−14 h at 80 °C, unless otherwise noted. [b] Isolated yields. NMR yields in parentheses. [c] Regioisomeric ratios for the cis-isomers. [d] Total cis/trans ratios determined by ¹H NMR. [e] The alkyne was added at once from the beginning of the reaction instead of the slow addition.

remarked that the silyl-substituted alkynylborane **1d** afforded the corresponding addition product in high yield (entry 11).

We then pursued the reactions of the silyl-substituted alkynylborane **1d**, which showed the highest reactivity. Use of Cy₃P in the reaction with 4-octyne resulted in almost quantitative formation of the corresponding alkynylboration product **4d** even with the lower catalyst (5 mol %) and alkyne (1.1 equiv) loadings (Table 2, entry 1). Reaction of dibenzylacetylene was then attempted under the same reaction conditions. We encountered a significant decrease in yield (<50% NMR yield) because of alkyne oligomerization as the major side reaction. It was found that the oligomerization was suppressed by "slow addition" of the alkyne to the mixture of the alkynylborane and the catalyst. Under the slow addition conditions, an improved yield was attained for the reaction of dibenzylacetylene (entry 2). The favorable effect of the slow addition protocol held for the reactions of unsymmetrical 1-aryl-1-alkynes. 1-Phenyl-1-propyne reacted with **1d**, giving cis-addition product in 57% yield (entry 3). The reaction proceeded regioselectively, affording 1-borylalk-1-en-3-yne **6** in which the aryl group is located at the 2-position. In a similar manner, 1-aryl-1-alkynes afforded the corresponding alkynylboration products in good yields with better regioselectivities (entries 4−9). Tolerability of the ester group as well as a terminal C≡C bond to the alkynylboration was proven (entries 8 and 9).

(2)
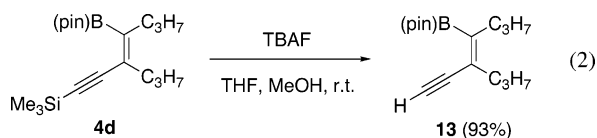
Treatment of the alkynylboration product **4d** with n-Bu₄NF allowed selective protodesilylation in high yield, giving **13** (eq 2). Highly substituted enynes **14** and **15** were prepared efficiently from the alkynylboration product **4d** via Suzuki−Miyaura coupling (Scheme 1).

The mechanism of the reaction is not clear at this moment. We presume that the reaction may proceed through the oxidative addition of the boron−carbon bond of the alkynylborane to the zerovalent nickel complex. Oxidative addition of boron−carbon bonds of arylboranes to nickel was proposed as one of the possible mechanisms of the hydroarylation of alkynes using arylboronic acids, though the boron atom is missing in the product.[13] A similar

Scheme 1. Suzuki-Miyaura Coupling of the Alkynylboration Product **4d**
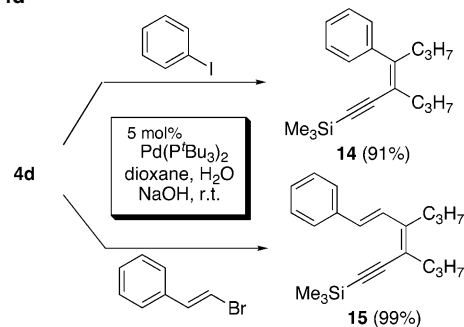
mechanism involving oxidative addition of element-alkynyl bond was proposed in the nickel-catalyzed alkynylstannation of alkynes.[11a,c]

In summary, addition of an alkynylborane to a carbon−carbon triple bond has been achieved by using a nickel catalyst. The cis-alkynylboration products are best obtained using PCy₃ or PCy₂Ph ligands with slow addition of the alkynes that undergo the addition. Mechanistic investigation, catalyst optimization, and synthetic application are now being undertaken in this laboratory.

Supporting Information Available: Experimental procedures and spectral data for the new compounds. This material is available free of charge via the Internet at http://pubs.acs.org.

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