Tetrahedron Letters 50 (2009) 3168–3170

Contents lists available at ScienceDirect

Tetrahedron Letters

journal homepage: www.elsevier.com/locate/tetlet

Palladium-catalyzed intramolecular cyanoboration of allenes leading to the regioselective synthesis of β-cyanoallylboranes

Akihiko Yamamoto, Yuto Ikeda, Michinori Suginome *

Department of Synthetic Chemistry and Biological Chemistry, Graduate School of Engineering, Kyoto University, Nishikyo-ku, Katsura, Kyoto 615-8510, Japan

ARTICLE INFO

Article history:
Received 15 December 2008
Revised 6 January 2009
Accepted 9 January 2009
Available online 14 January 2009

ABSTRACT

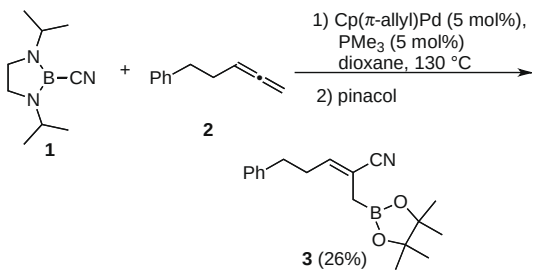
Inter- and intramolecular addition of the boron-cyanide bond of cyanoboranes across a carbon–carbon double bond of allenes proceeded in the presence of palladium catalysts, affording allylboranes that bear a cyano group at the β-position regioselectively.

Increasing attention has been focused on the efficient synthesis of functionalized organoboronic acids, which serve as useful synthetic intermediates in the synthesis of complex organic molecules.[1] Recent development of a variety of transformation reactions of organoboronic acids, such as Suzuki–Miyaura coupling,[2] rhodium-catalyzed conjugate addition,[3] and Petasis reaction,[4] has enhanced their utilities in organic synthesis. Further development of more efficient and convenient method for their synthesis is eagerly desired to take full advantages of organoboronic acids as synthetic intermediates. Of particular interest is transition-metal-catalyzed synthesis of organoboronic acids, which may provide synthetic routes to new organoboron compounds that are hardly accessible by other means. Catalytic additions of boron-containing σ-bonds to carbon–carbon multiple bonds are highly attractive, since the reactions are not only atom-economical but also allow regio- and stereoselective introduction of additional functionalities into the organic frameworks in one step.[5–8]

Our recent research interest has focused on the transition metal-catalyzed carboboration reactions in which carbon–carbon bonds are formed along with the boron–carbon bonds.[9–12] We found that the boron–cyanide bonds of cyanoboranes[13] are activated by palladium or nickel complexes, leading to cyanoboration of alkynes, which offers a unique synthetic access to β-boryl-α,β-unsaturated nitriles with high regio- and stereoselectivities.[10] These results prompted us to find a new addition reaction of cyanoboranes to other unsaturated organic molecules. In this report, we wish to describe the new synthesis of β-cyanoallylborane derivatives by cyanoboration of allenes.

Our study was initiated with intermolecular reactions of cyanoboranes with terminal allenes in the presence of palladium or nickel catalysts. After several attempts, we found that cyanoborane **1** reacted with allene **2** at 130 °C in the presence of 5 mol % of a palladium catalyst with trimethylphosphine (5 mol %), giving allylborane products albeit in low yield (Scheme 1). Although being insufficient in terms of yield, the addition reaction selectively afforded (*E*)-β-cyanoallylborane **3** along with minor formation of other isomers. In spite of our further trials, however, no significant improvement of the reaction yield could be made by the modification of the original reaction conditions. We then turned our attention to an intramolecular variant, which was found successful in the cyanoboration of alkynes.[10a]

The aminocyanoboryl ether **4a** was prepared by reaction of 1,1-diphenyl-3,4-pentadien-1-ol with cyanobis(diisopropylamino)borane. The cyanoboryl ether **4a** in toluene was heated in the presence of palladium or nickel catalysts bearing phosphine ligands. We found that addition of the B–CN bond across the tethered allene moiety proceeded at 80 °C in the presence of a Pd/PMe_3 catalyst (Table 1, entry 1).[14] The addition took place in a regioselective fashion at the internal C=C bond to provide 5-membered allylborane **5a** in 98% yield as a sole product.[15] It should be noted that some other ligands such as tricyclohexylphosphine, triphenylphosphine, and 2,2′-bipyridyl also served as effective ligands in the intramolecular cyanoboration (entries 2–4). We realized that a comparable yield was attained even in the absence of ligand (entry 5). This result may indicate that the phosphine ligands do not have strong influence on the efficiency of the reaction. However, we found bidentate ligands such as DPPP

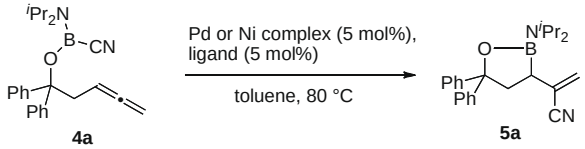


Scheme 1.

* Corresponding author. Tel.: +81 75 383 2723; fax: +81 75 383 2722.
E-mail address: suginome@sbchem.kyoto-u.ac.jp (M. Suginome).

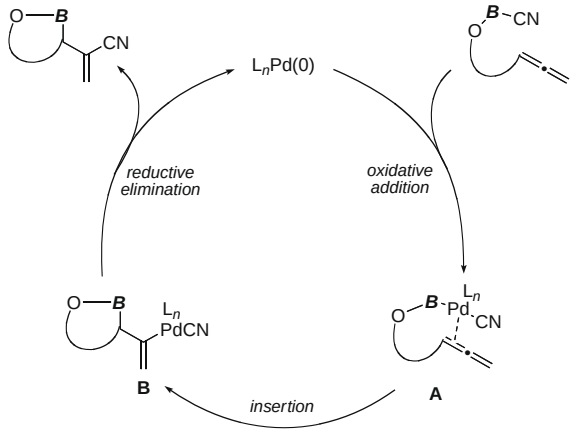
0040-4039/$ - see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.tetlet.2009.01.025

Table 1
Catalyst screening for intramolecular cyanoboration of **4a**[a]



Entry	Metal complex	Ligand	Time (h)	Yield[b] (%)
1	Cp(π-allyl)Pd	PMe_3	13	98
2	Cp(π-allyl)Pd	PCy_3	16	85
3	Cp(π-allyl)Pd	PPh_3	16	99
4	Cp(π-allyl)Pd	bpy	18	98
5	Cp(π-allyl)Pd	—	13	95
6	Cp(π-allyl)Pd	DPPP	13	13
7	Cp(π-allyl)Pd	$P(OMe)_3$	24	0
8	$Ni(cod)_2$	PMe_3	24	0

[a] A mixture of **1a** (29 mg, 0.12 mmol), metal complex (6.0 μmol), and ligand (6.0 μmol) was heated in toluene (0.2 mL) at 80 °C.
[b] NMR yield using dibenzyl ether as a standard.



Scheme 2. A possible mechanism of Pd-catalyzed intramolecular cyanoboration of allenes (***B***: $B(N^iPr_2)$). The other mechanistic possibility in which the internal C=C bond in **A** inserts into the Pd–CN bond is not shown.

and phosphite ligands such as $P(OMe)_3$ retarded the reaction significantly (entries 6 and 7). The combination of $Ni(cod)_2$ and PMe_3 completely failed to give the cyclization product (entry 8).

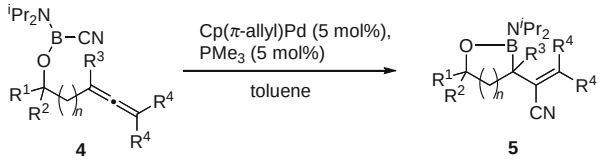
Other cyanoboryl ethers **4b–g** were subjected to the cyanoboration reaction in the presence of the Pd/PMe_3 catalyst (Table 2).[16] Cyanoboryl ethers **4b–d** bearing monosubstituted allenyl groups afforded the cyclized products **5b–d** (entries 1–3). It should be noted that the use of cyanoboryl ethers derived from tertiary alcohols was found to be crucial for the intramolecular cyanoboration to proceed. Attempted reactions of cyanoboryl ethers derived from *secondary* and *primary* alcohols resulted in no product formation. Intramolecular cyanoboration of **4e**, which carried two terminal methyl groups at the allenyl moiety, also gave product **5e** in high yield (entry 4). In contrast, attempted cyanoboration with an allenyl substrate **4f** bearing a geminally disubstituted allenyl group resulted in no reaction (entry 5). Cyanoboryl ether **4g** derived from a homologous allenyl alcohol gave 6-exo cyclized product **5g** in good yield (entry 6). All the cyanoboration products were found to be thermally stable and distillable, although further purification by silica gel chromatography was not possible due to their hydrolytic instability.

In all cases, the intramolecular cyanoboration provided allylboranes, which were formed through addition to the internal C=C bonds of allenyl groups with C–CN bond formation at the central carbon atoms of allenes. A possible mechanism is presumed as follows (Scheme 2): The B–Pd bond of the borylpalladium cyanide intermediate **A**, which is formed through oxidative addition of the B–CN bond to palladium(0) species, undergoes intramolecular insertion of the internal C=C bond of the allenyl group. The terminal C=C bond may hardly coordinate to palladium due to the considerable ring strain. Insertion into either the B–Pd bond or the Pd–CN bond followed by reductive elimination gives cyanoboration product **5**. In our mechanistic study on the alkyne cyanoboration,[10c] the B–Pd bond was found much more prone to undergo migratory insertion than the Pd–CN bond, although no decisive evidence as to the mode of insertion was obtained for the present cyanoboration of allenes.

The cyanoboration products have an allylborane substructure with a cyano group at their β-positions, being expected to serve as new β-cyanoallylation reagents. Since the products were not easily isolable, one-pot, sequential cyanoboration/allylation was attempted. The cyanoboration products **5a**, **5c**, and **5g** in the crude cyanoboration mixtures were reacted with benzaldehyde (Scheme 3). For instance, **5a** gave homoallyl alcohol **6a** in 83% overall yield for the two steps. The allylboration step required 110 °C (6 h) to complete. The enediol product **6a** was obtained as a single isomer with (*E*)-C=C bond, whose geometry was determined by nOe experiments. Allylboranes **5c** and **5g** also provided enediols **6c** and **6g** in 64% and 63% yields, respectively, with high stereoselectivity for the (*E*)-isomers.

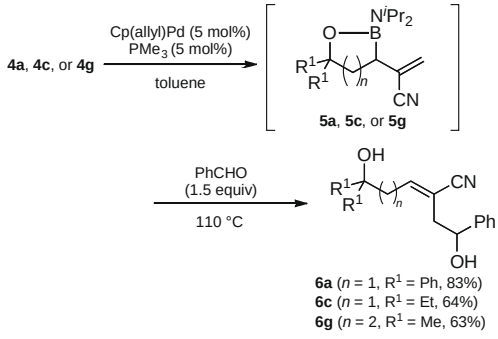
In summary, palladium-catalyzed cyanoboration of allenes has been demonstrated. Although intermolecular variant was not efficient, intramolecular cyanoboration of 3,4-alkadien-1-ol and 4,5-alkadien-1-ol derivatives proceeded at their internal C=C bond, providing β-cyanoallylboranes through 5- or 6-exo-cyclizations.

Table 2
Palladium-catalyzed intramolecular cyanoboration of **4**[a]



Entry	4	*n*	R^1,R^2	R^3	R^4	Temp (°C)	Product [yield%][b]
1	**4b**	1	Me, Me	H	H	80	**5b** [80 (64)]
2	**4c**	1	Et, Et	H	H	80	**5c** [74]
3	**4d**	1	$-(CH_2)_4-$	H	H	130	**5d** [49]
4	**4e**	1	Me, Me	H	Me	80	**5e** [98 (83)]
5	**4f**	1	Me, Me	Me	H	130	— [0]
6	**4g**	2	Me, Me	H	H	130	**5g** [86]

[a] A mixture of **4**, Cp(π-allyl)Pd (5 mol %), and PMe_3 (5 mol %) was heated in toluene.
[b] NMR yield using dibenzyl ether as a standard. Isolated yield in the parentheses.



Scheme 3. One-pot intramolecular cyanoboration/β-cyanoallylation for the synthesis of diols **6**.

The β-cyanoallylboranes reacted with aldehydes to give β-cyanoallylation products stereoselectively.

Acknowledgments

This work was supported by a Grant-in-Aid for Scientific Research on Priority Areas 'Advanced Molecular Transformations of Carbon Resources' from the Ministry of Education, Culture, Sports, Science, and Technology, Japan. A.Y. thanks JSPS for the fellowship support.

References and notes

1. Hall, D. G. *Boronic Acids*; Wiley, Weinheim: Germany, 2005.
2. (a) Miyaura, N. *Top. Curr. Chem.* **2002**, *219*, 11; (b) Suzuki, A.; Brown, H. C.. In *Organic Synthesis via Boranes*; Aldrich: Milwaukee, WI, 2003; Vol. 3; (c) Miyaura, N.; Suzuki, A. *Chem. Rev.* **1995**, *95*, 2457.
3. (a) Sakai, M.; Hayashi, H.; Miyaura, N. *Organometallics* **1997**, *16*, 4229; Reviews: (b) Fagnou, K.; Lautens, M. *Chem. Rev.* **2003**, *103*, 169; (c) Hayashi, T.; Yamasaki, K. *Chem. Rev.* **2003**, *103*, 2829.
4. (a) Petasis, N. A.; Akritopoulou, I. *Tetrahedron Lett.* **1993**, *34*, 583; (b) Petasis, N. A.; Zavialov, I. A. *J. Am. Chem. Soc.* **1997**, *119*, 445.
5. For B–H bond additions, see: (a) Nöth, H.; Männig, D. *Angew. Chem., Int. Ed. Engl.* **1985**, *24*, 878; (b) Hayashi, T.; Matsumoto, Y.; Ito, Y. *J. Am. Chem. Soc.* **1989**, *111*, 3426; Review: (c) Beletskaya, I.; Pelter, A. *Tetrahedron* **1997**, *53*, 4957.
6. For B–B bond additions, see: (a) Ishiyama, T.; Nishijima, K.-i.; Miyaura, N.; Suzuki, A. *J. Am. Chem. Soc.* **1993**, *115*, 7219; Review: (b) Ishiyama, T.; Miyaura, N. *J. Organomet. Chem.* **2000**, *611*, 392.
7. For B–Si bond additions, see: (a) Suginome, M.; Nakamura, H.; Ito, Y. *J. Chem. Soc., Chem. Commun.* **1996**, 2777; (b) Suginome, M.; Ohmura, T.; Miyake, Y.; Mitani, S.; Ito, Y.; Murakami, M. *J. Am. Chem. Soc.* **2003**, *125*, 11174; (c) Suginome, M.; Ito, Y. *J. Organomet. Chem.* **2003**, *680*, 43. and references therein.
8. For reviews on B-element bond additions, see: (a) Beletskaya, I.; Moberg, C. *Chem. Rev.* **2006**, *106*, 2320; (b) Suginome, M.; Matsuda, T.; Ohmura, T.; Seki, A.; Murakami, M.. In Crabtree, R., Mingos, M., Eds.; Comprehensive Organometallic Chemistry III; Ojima, I., Ed.; Elsevier, 2007; Vol. 10, p 725.
9. For uncatalyzed carboborations, see: Mihailov, B. M.; Bubnov, Y. N. *Tetrahedron Lett.* **1971**, 4597; See also: Knochel, P.. In *Comprehensive Organic Synthesis*; Trost, B. M., Ed.; Pergamon Press: Oxford, 1991; Vol. 4, p 865.
10. Ni- and Pd-catalyzed cyanoborations: (a) Suginome, M.; Yamamoto, A.; Murakami, M. *J. Am. Chem. Soc.* **2003**, *125*, 6358; (b) Suginome, M.; Yamamoto, A.; Murakami, M. *Angew. Chem., Int. Ed.* **2005**, *44*, 2380; (c) Suginome, M.; Yamamoto, A.; Sasaki, T.; Murakami, M. *Organometallics* **2006**, *25*, 2911; (d) Ohmura, T.; Awano, T.; Suginome, M.; Yorimitsu, H.; Oshima, K. *Synlett* **2008**, 423.
11. Ni-catalyzed alkynylboration: Suginome, M.; Shirakura, M.; Yamamoto, A. *J. Am. Chem. Soc.* **2006**, *128*, 14438.
12. Catalytic carboborations through activation of B–Cl bond with use of organometallic compounds as donors of organic group: (a) Suginome, M.; Yamamoto, A.; Murakami, M. *J. Am. Chem. Soc.* **2005**, *127*, 15706; (b) Daini, M.; Yamamoto, A.; Suginome, M. *J. Am. Chem. Soc.* **2008**, *130*, 2918; (c) Daini, M.; Suginome, M. *Chem. Commun.* **2008**, 5224.
13. Bu_2BCN: (a) Evers, E. C.; Freitag, W. O.; Kriner, W. A.; MacDiarmid, A. G. *J. Am. Chem. Soc.* **1959**, *81*, 5106; H_2BCN: (b) Spielvogel, B. F.; Bratton, R. F.; Moreland, C. G. *J. Am. Chem. Soc.* **1972**, *94*, 8598; Bis(dialkylamino)-cyano-boranes: (c) Bessler, V. E.; Goubeau, J. *Z. Anorg. Allg. Chem.* **1967**, *352*, 67; (d) Meller, A.; Maringgele, W.; Sicker, U. *J. Organomet. Chem.* **1977**, *141*, 249; (e) Suginome, M.; Yamamoto, A.; Ito, Y. *Chem. Commun.* **2002**, 1392.
14. One-pot intramolecular cyanoboration of 1,1-diphenyl-3,4-pentadien-1-ol with cyanobis(diisopropylamino)borane did not afford cyanoboration product **5a**, in spite of the fact that the corresponding one-pot intramolecular cyanoboration of alkynes was found successful as reported previously.[10a]
15. Spectral and analytical data for the selected new compounds. Compound **5a**: ^{1}H NMR (C_6D_6) δ 0.88 (d, J = 6.4 Hz, 3H), 1.05 (d, J = 6.4 Hz, 3H), 1.47 (d, J = 6.8 Hz, 3H), 1.51 (d, J = 6.8 Hz, 3H), 2.15 (t, J = 8.8 Hz, 1H), 2.62–2.73 (m, 2H), 3.00 (sept, J = 6.4 Hz, 1H), 3.41 (sept, J = 6.8 Hz, 1H), 4.82 (s, 1H), 5.13 (s, 1H), 6.95–7.02 (m, 2H), 7.08–7.18 (m, 4H), 7.43–7.53 (m, 4H); ^{13}C NMR (C_6D_6) δ 21.9, 22.7, 24.7, 44.6, 45.9, 49.5, 88.8, 119.4, 126.25, 126.33, 126.9, 127.36, 127.41, 128.79, 128.85, 147.6, 148.2; ^{11}B NMR (C_6D_6) δ 33.0; HRMS (EI) Calcd for $C_{24}H_{29}BN_2O$: 372.2373; Found: 372.2377. Compound **5b**: ^{1}H NMR (C_6D_6) δ 0.93 (d, J = 6.8 Hz, 3H), 1.04 (d, J = 6.0 Hz, 3H), 1.05 (s, 3H), 1.25 (s, 3H), 1.36 (d, J = 6.4 Hz, 3H), 1.39 (d, J = 6.8 Hz, 3H), 1.66–1.77 (m, 2H), 2.17 (t, J = 8.8 Hz, 1H), 2.94 (sept, J = 6.4 Hz, 1H), 3.38 (sept, J = 6.8 Hz, 1H), 5.06 (s, 1H), 5.24 (s, 1H); ^{13}C NMR (C_6D_6) δ 22.0, 22.7, 24.1, 24.3, 30.2, 30.7, 34.0–36.5 (br), 44.5, 44.9, 49.2, 81.5, 119.5, 127.9, 128.6; ^{11}B NMR (C_6D_6) δ 32.1; HRMS (EI) Calcd for $C_{14}H_{25}BN_2O$: 248.2056; Found: 248.2063. Compound **5c**: ^{1}H NMR (C_6D_6) δ 0.78 (t, J = 7.2 Hz, 3H), 0.92 (t, J = 7.2 Hz, 3H), 0.94 (d, J = 6.8 Hz, 3H), 1.06 (d, J = 6.8 Hz, 3H), 1.32 (q, J = 7.6 Hz, 2H), 1.36 (d, J = 6.8 Hz, 3H), 1.41 (d, J = 6.8 Hz, 3H), 1.48–1.61 (m, 2H), 1.65–1.75 (m, 2H), 2.15 (t, J = 9.6 Hz, 1H), 2.94 (sept, J = 6.8 Hz, 1H), 3.39 (sept, J = 6.8 Hz, 1H), 5.02 (s, 1H), 5.22 (s, 1H); ^{13}C NMR (C_6D_6) δ 8.9, 22.0, 22.7, 24.2, 24.3, 33.1, 33.3, 40.4, 44.4, 49.1, 86.6, 119.5, 127.5, 128.8; ^{11}B NMR (C_6D_6) δ 32.0; HRMS (EI) Calcd for $C_{16}H_{29}BN_2O$: 276.2373; Found: 276.2376. Compound **5e**: ^{1}H NMR (C_6D_6) δ 0.98 (d, J = 6.8 Hz, 3H), 1.11 (s, 3H), 1.12 (d, J = 6.0 Hz, 3H), 1.38 (s, 6H), 1.42 (d, J = 6.8 Hz, 3H), 1.49 (d, J = 6.8 Hz, 3H), 1.79 (s, 3H), 1.68–1.86 (m, 2H), 2.48 (t, J = 9.6 Hz, 1H), 3.00 (sept, J = 6.8 Hz, 1H), 3.35 (sept, J = 6.8 Hz, 1H); ^{13}C NMR (C_6D_6) δ 20.1, 22.1, 22.9, 24.2, 24.3, 24.7, 30.0, 31.0, 44.5, 44.7, 49.3, 81.2, 114.7, 119.7, 147.5; ^{11}B NMR (C_6D_6) δ 32.7; HRMS (EI) Calcd for $C_{16}H_{29}BN_2O$: 276.2373; Found: 276.2366. Compound **6a**: ^{1}H NMR ($CDCl_3$) δ 2.47 (dd, J = 4.0, 14.4 Hz, 1H), 2.83 (dd, J = 9.2, 14.4 Hz, 1H), 3.10 (dd, J = 6.0, 14.4 Hz, 1H), 3.23 (dd, J = 9.2, 14.4 Hz, 1H), 4.93 (dd, J = 3.6, 9.2 Hz, 1H), 6.35 (dd, J = 6.4, 8.8 Hz, 1H), 7.23–7.41 (m, 15 H); HRMS (Cl^+) Calcd for $C_{25}H_{22}NO$ (MH^+–H_2O): 352.1701; Found: 352.1700. Compound **6c**: ^{1}H NMR ($CDCl_3$) δ 0.86 (t, J = 7.6 Hz, 3H), 0.89 (t, J = 7.2 Hz, 3H), 1.49 (q, J = 7.2 Hz, 2H), 1.50 (q, J = 7.2 Hz, 2H), 2.18 (dd, J = 6.8, 14.8 Hz, 1H), 2.40 (dd, J = 9.2, 14.8 Hz, 1H), 2.49 (dd, J = 4.0, 14.4 Hz, 1H), 2.82 (dd, J = 9.2, 14.0 Hz, 1H), 5.00 (dd, J = 4.0, 9.2 Hz, 1H), 6.60 (dd, J = 8.4, 9.2 Hz, 1H), 7.29–7.40 (m, 5H); HRMS (Cl^+) Calcd for $C_{17}H_{24}NO_2$ (MH^+): 274.1807; Found: 274.1816. Compound **6g**: ^{1}H NMR ($CDCl_3$) δ 1.19 (s, 6H), 1.36 (ddd, J = 5.6, 9.6, 13.6 Hz, 1H), 1.48 (ddd, J = 6.0, 9.6, 13.6 Hz, 1H), 2.06–2.16 (m, 1H), 2.21–2.32 (m, 1H), 2.54 (dd, J = 5.2, 14.4 Hz, 1H), 2.77 (dd, J = 8.0, 14.0 Hz, 1H), 4.98 (dd, J = 5.6, 8.4 Hz, 1H), 6.46 (dd, J = 7.2, 8.0 Hz, 1H), 7.29–7.41 (m, 5H)); HRMS (Cl^+) Calcd for $C_{16}H_{22}NO_2$ (MH^+): 260.1651; Found: 260.1650.
16. Other catalyst systems suggested as such in Table 1 including the ligandless system (Table 1, entry 5) may be similarly used as the catalysts for the intramolecular cyanoboration.